Advanced C++ Libraries and Introduction to Template Metaprogramming

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Advanced C++ Libraries and Introduction to Template Metaprogramming

		Lectures	Labs
J1	4:00-4:30	1. Introduction 2. Template reminder and complements 3. Smart pointers 4. High order programming: only bind()	
	2:00-2:30		Lab 1: Polymorphic collections Lab 2: Logger (optional)
J2	2:30	4. Type traits 4. High order programming: function<>, lambdas	
	2:00		Lab 4: Type traits
	1:30	5. Boost containers and algorithms	
	1:00		Lab 5: boost::any
J3	1:30	6. Strings and regular expressions	
	2:00		Lab 3: Regex
	1:00	7. Boost serialization	
	1:30		Lab 6: Serialization
	1:00	8. Introduction to the metaprogramming library (MPL)	

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Part 1

Introduction

Introduction

- **Generative programming**
- **TR1 and Boost C++ library extensions**
- **C++ extensions — Towards C++11**
- **References**

Generative Programming

- **Generative programming**
  - Programming the generation of programs
  - A very old practice in Computer Science
- **Metaprogramming**
  - Generative programming where the generative language and the target language are the same
  - The language must have *reflection* capabilities
- **Template (meta)programming**
  - Metaprogramming *à la* C++
    - The generative language is the template subset of C++
    - The target language is full C++

C++ STL Extensions: TR1

- **Part of future C++ Standard (C++11)**
  - Available (partially) with most current implementations
  - For the most part, already in Boost

- **General utilities (reference wrappers, smart pointers)**
- **Function objects (`mem_fn`, `bind`)**
- **Type traits**
- Numerical facilities (random numbers, special functions)
- **Containers (`tuple`, `array`, unordered associative containers)**
- **Regular expressions (`regex`)**
- Improved C99 compatibility

C++ STL Extensions: Boost

- **Open source**
  - Boost Software License
- **Extensions of the STL**
  - Respect basic philosophy
  - Many sub-libraries
    - Different themes
    - Different sizes
- **Work on most C++ compilers**
- **Large library**
  - Usable by pieces...
- **Some parts integrated into TR1**

- **String and text processing**
- **Containers, iterators, algorithms**
- **Function objects, high order programming**
- **Generic and template metaprogramming**
- Preprocessor metaprogramming
- Concurrent programming (Thread)
- Maths and numerics
- Correctness and testing
- Data structures, graphs (Graph)
- Image processing (GIL)
- **Input/output (ASIO, serialization...)**
- Inter-language support (Python)
- Memory handling
- Parsing (Spirit)
- Programming facilities...

C++ Extensions: Towards C++11

- **The future version of C++ (C++11) will propose many extensions to C++**
  - Some of these extensions are already available with some compilers
- **Extensions of C++11 used in the examples of this course (g++4.7.x+)**
  - Inclusion of the *Technical Report 1* (TR1) into namespace `std`
  - Fix for the >> problem: `A<B<int>>`
  - Static assertion: `static_assert(c, "message");`
    - *c* must be a compile time expression convertible into `bool`
    - We use our macro `STATIC_ASSERT(c)` where the message is empty
  - New initialization syntax: `vector<int> v = {1, 2, 3, 4};`
  - Auto typing: `auto x = expr`
  - Range-based `for` loop: `for (auto e : container) { … }`
  - Lambda expressions
  - True null pointer: `nullptr`
  - Defaulted and deleted member functions:

```
A(const A&) = delete;  // class not copy constructible
A() = default;         // provide the default default constructor
```


C++11, Boost, and TR1

- **Boost contains a (large) subset of TR1**
  - Some notational differences
  - Different header file organization
- **Namespaces**
  - Before C++11, TR1 extensions reside in namespace `::std::tr1`
  - In C++11, TR1 extensions are directly in `::std`
  - On the slides, we usually forget namespace qualification (`using namespace`…)
- **Program excerpts in this course**
  - When applicable, TR1 is preferred to Boost
  - The C++ compiler is **gcc-4.7** or more recent
  - Compilation uses **C++11 compatibility**: `-std=c++11`
  - Boost version is **boost-1_49_0**

References

- **Generative Programming: Methodes, Tools, and Applications**
  Krzysztof Czarnecki, Ulrich Eisenecker — Addison Wesley, 2000 [General]
- **C++ Templates: The Complete Guide**
  David Vandevoorde, Nicolai Josuttis — Addison Wesley, 2003 [General]
- **Modern C++ Design: Generic Programming and Design Patterns Applied**
  Andrei Alexandrescu — Addison Wesley, 2001 [General]
- **The C++ Standard Library Extensions: A Tutorial and Reference**
  Pete Becker — Addison Wesley, 2006 [tr1]
- **Beyond the C++ Standard Library**
  Björn Karlsson — Addison Wesley, 2006 [Boost]
- **C++ Template Metaprogramming: Concepts, Tools, and Techniques from Boost and Beyond**
  David Abrahams, Aleksey Gurtovoy — Addison Wesley, 2005 [Boost mpl]
- **Proposed Draft Technical Report on C++ Library Extensions**
  ISO/IEC PDTR 19769, 2005 [tr1]
- **Boost Library Documentation**
  http://www.boost.org/ [Boost]
- **The MPL Reference Manual**
  http://www.boost.org/doc/libs/1_40_0/libs/mpl/doc/tutorial/reference-manual.html [Boost mpl]

Advanced C++ Libraries and Introduction to Template Metaprogramming

Part 2

C++ Template Reminder

C++ Templates

- **Class and function templates overview**
  - Definition and use
  - Template parameters
- **Template specialization**
  - Full specialization of class and function templates
  - Partial specialization of class templates
  - Consequences of specialization on name lookup
  - TURING-completeness of C++ templates
- **Overloading resolution**
  - Overview
  - Argument deduction
    - SFINAE: *Substitution Failure Is Not An Error*

Class and Function Templates

- **Functions and classes templates parameterized (principally) with types**
- **Two different mechanisms for functions and classes**
  - Although somewhat homogenized by ANSI C++
- **Static resolution (compile and link time)**
  - The template parameters must be static entities
  - A type driven macro-processing facility
- **A full programming language on top of (template-less) C++**

Function Templates

- **Definition of function templates**

```
template <typename T>
T Min(T a, T b) {
   return a < b ? a : b;
}
```

  - Constraints on template parameters (`T`) are implicit (“Duck Typing”)
- **Use of function templates**
  - Parameterized overloading

```
int x, y, z; . . .; z = Min(x, y);
string s1, s2, s; . . .; s = Min(s1, s2);
```

  - Explicit instantiation

```
int u = Min<double>(x, 5.7);
```


Class Templates

- **Definition of a class template**

```
// File: List.h

template <typename T>
class List {
public:
  List();
  void append(const T&);
  . . .
};
```

- **Use of a class template**

```
// File xxx.cpp

List<int> aList;
. . .
aList.append(3);
```

- **Definition of the members of a class template**

```
// File: List.cppList.h

template <typename T>
List<T>::List() {
  . . .
}

template <typename T>
void List<T>::append(
             const T& t) {
  . . .
}

. . .
```

Class Templates and Implicit Conversions (1)

- **Template instances and implicit conversion**
  - Since there exists an implicit conversion from `int` to `double`, shouldn't be a `List<int>` implicitely convertible into a `List<double>`?
  - Since a French is a Human (suppose), shouldn't a set of French be implicitely convertible into a set of Human?
  - The answer is NO in both cases
    - Should the answer be yes, substitutability principle, contravariance rule, and static type checking would be broken...
- **Two instances of the same class template define different types as soon as their (effective) template parameters are different**

Class Templates and Implicit Conversions (2)

- **Breaking static type checking ?**
  - Assume `French` (and `English`) derives from `Human`
  - Hence, `French *` is implicitely convertible into `Human *`
  - Suppose we allow implicit conversion from `set<French *>` to `set<Human *>`
  - Static typing is broken!

```
void f(set<Human *>& sh) {
  sh.insert(new English());
    // OK since English are
    // Human, after all
}

set<French *> sf;
// ...
f(sf);// implicit conversion
  // There is now an English
  // among the French!
```


Member Function Template (1)

- **Member template of a regular class**

```
class A {
public:
  template <typename U> void mt(U u);
};

template <typename U> void A::mt(U u) { ... }
```

- **Just a parameterized overloaded member function**

```
A a;
a.mt(3);       // A::mt(int)
a.mt("hello"); // A::mt(char *)
a.mt(3.5);     // A::mt(double)
```


Member Function Template (2)

- **Member template of a class template**

```
template <typename T>
class A {
public:
  template <typename U> void mt(U u);
};

template <typename T>
template <typename U>
void A<T>::mt(U u) { ... }

A<int> a;
a.mt("hello"); // A<int>::mt(char *)
```

- **Member templates cannot be virtual**

Class Template and Friendship (1)

- **The friend function does *not* depend on the template parameters, in any possible way**
  - Friendship with *all* (visible) instances of the template

```
template <typename T>
class A {
  friend void f();
private:
  int _i;
  // ...
};

void f() {
  A<int> ai;
  A<string> as;
  A<A<double> > aad;
  ai._i = 10;   // OK
  as._i = 10;   // OK
  aad._i = 10;   // OK
}
```


Class Template and Friendship (2)

- **The friend function does depend on (some of) the template parameters**
  - Friendship only with instances of the template with the same effective template arguments

```
template <typename T>
class A {
  friend void f(A<T> a) {
    A<int> ai;
    A<T> at;
    ai._i = 10; // NO if T
                // is not int
    a._i = 10;    // OK
    at._i = 10;   // OK
  }
private:
  int _i;
  // ...
};

int main() {
  A<string> as;
  f(as);
}
```


Class Template and Friendship (3)

- **Defining a friend function of a class template**
  - outside the class
    - The function must be declared before the class
    - The friend declaration must specify that a function specialization is intended
    - The friend function may be (often, must be) defined after the class
  - within the class
    - The function is not injected into the global namespace
    - But it will be found by *Argument Dependent Lookup* (see namespaces)

```
template <typename T>
void g(T t);

template <typename T1, typename T2>
class A {
  friend void g<T1>(T1);
  // friend void g<>(T1); enough
here

  friend void h(T1 t1) {
    // ...
  }
};

template <typename T>
void g(T t) {
  // ...
}
```


Class Template and Friendship (4)

- **Friend function template of a regular class**

```
class A {
  template <typename U> friend void tf(U u);
  // ...
};
template <typename U> void tf(U u, ...) { ... }
```

- **Friend function template of a class template**

```
template <typename T>
class A {
  template <typename U> friend void tf(U u)
  { ... } // must be defined inline!
  // ...
};
```

Class Template and Friendship (5)

- **Friend class template of a regular class**

```
class A {
  template <typename>
  friend class F;
private:
  int _i;
};

template <typename T>
class B {
  template <typename>
  friend class F;
private:
  T _t;
};
```

```
template <typename U>
class F {
public:
  void m() {
    A a;
    a._i = 12;   // OK
    B<int> b1;
    b1._t = 6;   // OK
    B<U> b2;
    b2._t = U(); // OK
  }
};

int main() {
  F<double> fr;
  fr.m();
}
```


Template parameters of templates (1)

- **ISO C++ unifies the template parameter possibilities for template functions and classes**
- **A generic parameter may be**
  - A type (built-in or class)
  - A static constant of any integral type
    (this includes enumerations and also pointers to members and pointers to **extern** variables and functions
  - Another class template
- **Default values are possible for template parameters**
  - But for class templates only, not for function templates (in C++03)

Template parameters of templates (2)

- **Pointers as template parameters**

```
template <typename T, void (*SORT)(int, T[])>
class Sorter {...};

extern void quicksort(int, double[]);
Sorter<double, quicksort> s(...);
```

  - Parameterize internal implementation (algorithms)
  - The pointed object must be `extern`

Template parameters of templates (3)

- **Class templates as template parameters**

```
template < typename U,
           template <typename, typename>
           class Container = std::vector >
class Something {
  Container<string, std::allocator<string> > _cs;
  Container<int, std::allocator<int> > _ci;
  // ...
};

template <typename T, typename A>
class My_Container {...};

Something<int, My_Container> sth1; // use My_Container
Something<double, std::list> sth2; // use std::list
Something<int> sth3;               // use default std::vector
```

  - Parameterize internal implementation (data structures)

Template parameters of templates (4)

- **Default values for template parameters**

```
template <typename T = int, int N = 10>
class Fixed_Array {...};

Fixed_Array<double, 100> fa1;
Fixed_Array<double> fa2; // Fixed_Array<double, 10>
Fixed_Array<> fa3;       // Fixed_Array<int, 10>
```

  - Rules are similar to default value for function parameters

Template parameters of templates (5)

- **Forbidden effective template parameters**
  - Local types (in C++ 2003)
  - Constants of type real
  - Non-extern pointers...

```
template <double X>  // NO
class B { ... };

const double PI = 3.41592;
B<PI> bpi; // NO
```

```
template <typename T>
class A { ... };

void f() {
  class L { ... };
  A<L> a; // NO in C++03
}
```

```
template <char *C>
class A { ... };
A<"hello"> a1; // NO

extern char c[];
  // initialize it somewhere
A<c> a2; // OK
```


Template Full Specialization

- **Full specialization of a function template**

```
template <typename T>
T Min(T a, T b) { . . . }

template <>
const char *Min<>(
     const char *s1,
     const char *s2)
{
  return strcmp(s1, s2) < 0
        ? s1 : s2;
}
```

  - The second `<>` is optional here (but not the first `<>`!)

- **Full specialization of a class template**

```
template <typename T>
class List { . . . };
```

  - a specialization of `List<T>` when `T` is a C-string

```
template <>
class List<char*> { . . . };
```

  - the contents and interface of `List<char*>` can be totally different from those of the generic `List<T>`

Class Template Partial Specialization

- **Partial specialization of a class template**

```
template <typename T>
class List { . . . };
```

  - a specialization of `List<T>` when `T` is a pointer

```
template <typename U>
class List<U*> { . . . };
```

  - the contents and interface of `List<U*>` can be totally different from those of the generic `List<T>`

Function Template Partial Specialization (1)

- **Both function and class templates can be fully specialized**
  - This includes member templates
- **Only class templates can be partially specialized**
  - Function and member templates cannot...
  - ... but they can be overloaded

```
template <typename T>
T Min(T a, T b) { . . . }
```

An overloaded form when `T` is a pointer

```
template <typename T>
T* Min(T* a, T* b) { . . . }
```

  - ~~C++11 will allow partial specialization of function templates~~
- **The specializations must be in the same namespace as the template definition**

Consequences of Specialization on Name Lookup (1)

- **Templates are parsed twice**
  - At the template definition
    - Verify basic syntax
    - Look up non-dependent names since they must have been already defined
  - At instantiation point
    - Where the compiler inserts the substituted template definition
    - Look up dependent names since their resolution required knowledge of effective template parameters
  - 2-phases lookup
- **Independent name**
  - A name that does not depend on any template parameter
- **Dependent name**
  - A name that depends on (some) template parameters

```
T::A
A<T>
A<T>::_i
C::m<T>

this
...
```


Consequences of Specialization on Name Lookup (2)

```
template <typename T>
struct A {
  int _i;
};

template <typename T>
struct B : A<T> {
  void f() {
    _i = 12; // compile error


  }
};

template <>
struct A<int> {
  // no definition for _i
};

B<int> b; // _i already bound?
```

```
template <typename T>
struct A {
  int _i;
};

template <typename T>
struct B : A<T> {
  void f() {
    _i = 12;
    A<T>::_i = 12;    // OK
    this->_i = 12;    // OK
  }
};

template <>
struct A<int> {
  // no definition for _i
};

B<int> b; // error detected OK
```


Consequences of Specialization on Name Lookup (3)

```
template <typename T>
struct A {
  struct C { . . . };
};

template <typename T>
class B : public A<T> {
  void f() {
    C c; // KO (see previous slide)
    A<T>::C c; // compile error

  }
};

void C(int);
template <>
struct A<int> {
  int c;
  void f() { C (c); . . .}
};
B<int> b; // C: type or function?
```

```
template <typename T>
struct A {
  struct C { . . . };
};

template <typename T>
class B : public A<T> {
  void f() {
    C c;
    A<T>::C c;
    typename A<T>::C c;// OK
    typename T::iterator it;
  }
};

void C(int);
template <>
struct A<int> {
  void f() { C (c); . . .}
};

B<int> b; // error detected OK
```

TURING-completeness of C++ Templates (1)

- **C++ offers two levels of languages**
  - C++ without templates, a classical programming language
with run-time semantics
  - The template mechanism itself
    - with compile-time semantics
- **Both levels are TURING-complete**
  - They make it possible to compute any *Computable Function*
  - Thus C++ Templates constitute a programming language whose programs are evaluated at compile-time
  - The power of C++ templates comes (in particular) from
    - integral template parameters
    - template specialization

TURING-completeness of C++ Templates (2)

- **Computing the FIBONACCI series at compile time with templates**

```
template <int N> struct Fibo {
    static const long long value =
          Fibo<N-1>::value + Fibo<N-2>::value;
}; // Generic form

template <> struct Fibo<0> {
    static const long long value = 1;
 }; // Specialization to stop recursion

template <> struct Fibo<1> {
    static const long long value = 1;
 }; // Specialization to stop recursion

int main() { // we still have to run to print out result!
    cout << Fibo<40>::value << endl;
}
```


TURING-completeness of C++ Templates (3)

- **Note that the computational complexity of `Fibo<N>` is linear**

Fibo(40)	Compilation	Run
Iterative	0.24	0.00
Recursive	0.24	2.34
Template	0.22	0.00
Intel Xeon at 2.33 GHz (times in seconds)		

Overloading Resolution (1)

- **Overview**
  - Given a function call, find a unique function with the same name matching the call

    `… f(a1, a2, ..., an) …`
    - `n` is known, as well as the argument types `T1`, `T2`, ..., `Tn`
    - Context and return type play no role
- **Overloading resolution principle**
  - Identify candidate functions using name lookup
  - Among candidate functions, select the viable ones, the ones that can correspond to the call
  - Among viable functions, select the best match for the call
    - Relies on ranking possible argument conversions

Overloading Resolution (2)

- **Implicit conversion strength**
  1. Exact match: strict exact match (identity) or *lvalue* transformations
  2. Qualification adjustment: adding `const` or `volatile`
  3. Integral and floating point promotions
  4. Integral and floating point conversions, pointer conversions, inheritance conversions
  5. User defined conversions: constructor, cast operator
     - at most one for each argument
- **The best viable function is the unique function, if it exists, such that**
  - the conversion applied to each argument is ***no worse*** than for all the other viable functions
  - there is ***at least one argument*** for which this function ***has a strictly better conversion*** that the other viable functions

Overloading Resolution (3)

- **Remarks on overloading resolution when template functions are candidates**
  - A template function is not a real function, but a potential infinity of them
  - Thus we need to select templates *instances*
  - However, the richness of C++ implicit conversions make the number of candidate instances huge, if not infinite
  - *Hence, the number of candidate instances has to be reduced*
- **Argument deduction**
  - The process of matching (substituting) the call arguments with the function template parameters
  - Only the following conversions are accepted
    - Exact match conversions
    - Qualification adjustment
    - Derived to base (inheritance) conversions

Overloading Resolution (4)

- **Overloading resolution when template functions are candidates**
  - Candidate functions
    - Add the function template instances for which argument deduction succeeds: parameter substitution
    - Select template specializations, if any, instead of generic form
  - Viable functions: unchanged
    - Candidates issued from templates are automatically viable
  - Best viable function
    - In case of ambiguity for the best viable between a template and a non template instance, select the non template
- **It is not an error for argument deduction (parameter substitution) to fail**
  - This simply means that no instance of the template function can match the call
    - but other functions—templates or not—may do so
  - SFINAE: *Substitution Failure is Not An Error*
    - Template programming often takes advantage of it
    - See in particular `boost::enable_if` later

Overloading vs. Function (Full) Specialization

- **Do not confuse specialization and overloading!**
  - The supported conversions are not the same...

```
template <typename T>
bool is_equal(const T& t1, const T& t2); // generic

template <>
bool is_equal(const string& t1, const string& t2); // specialize

bool is_equal(const string& t1, const string& t2); // override

bool b = is_equal("hello", "bonjour");
```

  - Specialization (*`specialize`*) does not match
    - it would require a user-defined conversion `const char*` → `string` forbidden in argument deduction context
  - Overloading (*`override`*) does match since user-defined conversion is valid here
    - and supersedes generic as well as all specialization forms

Part 3

Shared Pointers

Working with Pointers

- **Drawbacks of regular (C) pointers**
- **The *Resource Acquisition Is Initialization* idiom (RAII)**
- **Smart pointers and RAII; the infamous `auto_ptr`**
- **Boost and TR1 RAII pointers**
  - `boost::scoped_ptr`: a pure RAII smart pointer
  - `tr1::unique_ptr`: a replacement for `auto_ptr`
  - `tr1::shared_ptr`: a pointer to safely share (and delete) resources
  - `tr1::weak_ptr`: coping with circular data structures
  - Smart pointers and inheritance
- **Pros and cons of smart pointers**

Drawbacks of regular (C) pointers

```
void f() {
   int *pi = new int(3);
   int *pj = new int[3];
   // . . .
   delete pi;
   if (*pi == 0)
      throw Exc();
   else
      *pi = 12;
   // . . .
}
```

pointeurs to individual objects and to arrays are not distinguishable

when dynamically allocated, explicit deletion required...

... but when? this certainly compiles and runs...

but this may **crash**, and even if it does not, it is **incorrect**

`pj` is never deleted, hence **memory leak**

Resource Acquisition Is Initialization (RAII)

- **Use destructor to release a resource at the end of its scope**

```
class Lock {
  Mutex& _m;
public:
  Lock(Mutex& m) : _m(m) {_m.lock();}
  ~Lock() {_m.unlock();}
};
void f() {
  Lock l(the_mutex);
  ifstream is("foo.txt");
  // . . .
}
```

`~ifstream()` automatically flushes the buffer and releases all

`~Lock()` automatically releases the mutex

Smart Pointers and RAII

```
template<typename T>
class SP {
     T *_pt; // encapsulated pointer
public:
     SP(T *pt) : _pt(pt) {}
     // possibly other constructors
     ~SP() {if (needed) delete _pt;}
     // other operations: *, ->, casts…
};

class A { . . . };

void f() {
     SP<A> pa(new A());
     // work with pa as with a pointer
}
```

The condition for deleting the object may vary with the nature or role of the smart pointer

The object **must** be allocated with `new`

`~SP()` automatically deletes the `A` object if needed

Smart Pointer and RAII
The infamous `auto_ptr` (1)

- **In the standard library since 1998**
- **Copyable**
  - but with special (bizarre?) copy semantics
  - the pointer origin of the copy is set to zero and thus becomes invalid
  - the object pointed to is not sharable through several auto pointers
  - `auto_ptr` cannot be put into STL containers
- **The only "safe" copy context is returning an `auto_ptr` by value from a function**
- **Its use should be restricted to legacy code and only when copying is not needed.**

Smart Pointer and RAII
The infamous `auto_ptr` (2)

```
#include <memory>

class A { . . . };

void f(std::auto_ptr<A> ap);

void someFunction() {
     std::auto_ptr<A> ap1(new A());
     // work with ap1 as if it were a pointer

     std::auto_ptr<A> ap2(ap1); // ownership transfer (move)
         // the internal pointer of ap1 has been set to null

     f(ap2); // ownership transfer (move)
         // the internal pointer of ap2 has been set to null
}
```

The `A` object is deleted correctly (and only once) on exiting the function

Smart Pointer and RAII
The infamous `auto_ptr` (3)

```
std::auto_ptr<A> h() {
   std::auto_ptr<A> ap(new A());
   // . . .
   return ap;
}

void someFunction() {
   // . . .
   std::auto_ptr<A> ap1;
   ap1 = h();
   // . . .
   return;
}
```

Nothing is deleted here since `ap` has been set to null by the function return

Ownership of the `A` object transferred to `ap1`
In `h()`, `ap` set to null

The `A` object is deleted correctly (and only once) on exiting this function

Boost Scoped Pointer

- **A strict auto pointer, used only for RAII, not copyable**
  - The object pointed to cannot be shared

```
#include <boost/scoped_ptr.hpp>

void f(boost::scoped_ptr<A> ap); // NO: compile error

void someFunction() {
    boost::scoped_ptr<A> ap1(new A());
    // work with ap1 as if it were a pointer

    boost::scoped_ptr<A> ap2(ap1); // NO
    ap2 = ap1; // NO
}
```

The A object is deleted correctly on exiting the function

C++11 Unique Pointer (1)

- **A strict auto pointer, used only for RAII, not copyable**
  - The object pointed to cannot be shared
- **Usage identical to `boost::scoped_ptr`**

```
#include <memory>

void f(std::unique_ptr<A> ap); // NO: compile-time error

void someFunction() {
    std::unique_ptr<A> ap1(new A());
    // work with ap1 as if it were a pointer

    std::unique_ptr<A> ap2(ap1); // NO
    ap2 = ap1; // NO
}
```

The A object is deleted correctly on exiting the function

C++ 0x Unique Pointer (2)

- **By default, the pointed object is deleted by `operator delete`**
  - The pointed object must have been allocated by `new`
- **It is possible to pass a *deleter* function (or function-object) to the `unique_ptr` constructor**

```
class A { . . . };
void a_deleter(A *pa) { . . . }
. . .
void f() {
    A a; // or any other kind of allocation
    unique_ptr<A> pa(&a, &a_deleter);
    // . . .
}
```

  - Destruction of `pa` calls `a_deleter()` on the pointed object
  - In this case, `delete` and `~A()` are not used for deleting the pointed object
- **This makes it possible to release resources which are not allocated by `new` (or even which are not related to memory)**
- **`unique_ptr` supports C++11 *move semantics (ownership transfer)***

TR1 Smart Pointers

- **TR1 borrows and adapts two smart pointers from Boost**
  - `shared_ptr<T>`: reference counting smart pointer, copiable
  - `weak_ptr<T>`: a sort of pointer *observer*, to break circular data structures
- **Boost has other smart pointers which are not part of TR1 (nor of C++11)**
  - `scoped_ptr` replaced by `std::unique_ptr`
  - `scoped_array` and `shared_array`: no so useful
  - `intrusive_ptr`: sharing objects with an embedded reference count

TR1 Smart Pointers
Construction of `shared_ptr`

```
#include <memory> // for C++11
#include <tr1/memory> // for C++03 with TR1
using namespace std;
using namespace std::tr1; // for C++03 with TR1
```

- **Empty shared pointer**

```
shared_ptr<T> pt; // owns nothing
```

- **Pointer to a dynamically allocated object**

```
shared_ptr<T> pt(new T(constructor parameters)); // constructor explicit
auto pt = make_shared<T>(constructor parameters);
```

  - This constructor allocates a new reference count for the pointed object
  - Destruction is performed by `operator delete` on pointed object
- **Pointer to a resource which is not dynamically allocated, or which is not memory based, or ...**

```
void a_deleter(T *p) { . . . }
T t;  // or any other kind of allocation
shared_ptr<T> pt(&t, &a_deleter);
```

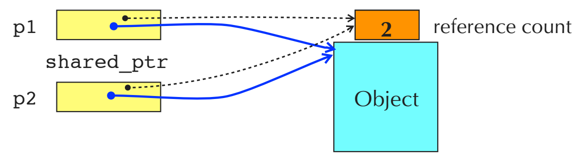
  - Destruction of `pt` calls `a_deleter()` on the pointed object
  - `delete` and `~T()` are not used for deleting the pointed object

TR1 Smart Pointers
`shared_ptr`

- **Smart pointer with reference counting**
  - The reference count is handled by the smart pointer, outside the object

The `shared_ptr` constructor allocates the reference count

  - Copiable: copy operations update the reference count
  - The `shared_ptr` destructor decrements the reference count and deletes the pointed object when the count becomes 0



TR1 Smart Pointers
Operations on `shared_ptr` (1)

- **`shared_ptr` are copiable objects**
  - Copy constructor and copy assignment
  - `shared_ptr` can be put into STL containers
- **Copy with conversion**
  - A `shared_ptr<U>` is implicitly convertible into a `shared_ptr<T>` provided that `U*` is implicitly convertible into `T*`
  - This is possible only if `U` derives from `T` (or if `T` is `void`)
- **Comparison operations**
  - Equality, unequality, relational operators
- **Display operation**
  - `operator<<` for `ostream`

TR1 Smart Pointers
Operations on `shared_ptr` (2)

- **Specific shared pointer member functions (1)**
  - `sp1.swap(sp2)` or `swap(sp1, sp2)`

Exchange the two pointed objects

  - `T* p = sp.get()`
    - Return the internal pointer (**dangerous! avoid it!**)
  - `T& rt = *sp`   (`operator*`)
    - Return a reference to the pointed object
  - `sp->f()`   (`operator->`)
    - Return the internal pointer so that a member can be selected
  - `long n = s.use_count();`
    - Return the current reference count
  - `if (sp.unique()) . . .`
    - Return whether the reference count of `sp` is 1 (unique owner)

TR1 Smart Pointers
Operations on `shared_ptr` (3)

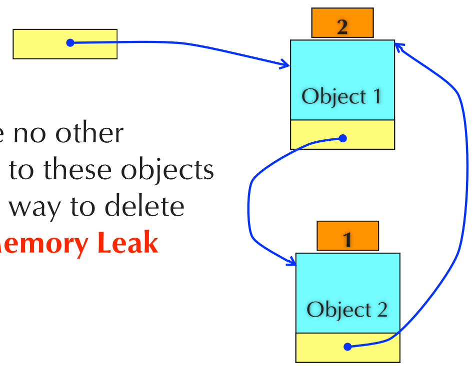
- **Specific shared pointer member functions (2)**
  - `sp.reset()`
    - Release ownership (decrement reference count)
    - Equivalent to: `shared_ptr().swap(*this)`
  - `sp.reset(p)` (`p` is a pointer to some object, possibly of different type)
    - Replace currently owned object by the one pointed by `p`
    - `p` must be convertible into the type of the internal pointer of `sp`
    - Equivalent to: `shared_ptr(p).swap(*this)`
  - `sp.reset(p, d)` (`p` is a pointer as above, `d` is a deleter)
    - Replace currently owned object by the one pointed by `p` with deleter `d`
    - `p` must be convertible into the type of the internal pointer of `sp`
    - Equivalent to: `shared_ptr(p, d).swap(*this)`
  - `sp.get_deleter()`
    - Return the address of the current deleter or 0 if not any

TR1 Smart Pointers
Operations on `shared_ptr` (4)

- **Conversion of shared pointers**
  - A `shared_ptr<U>` is implicitly convertible into a `shared_ptr<T>` provided that `U*` is implicitly convertible into `T*`
  - `spt = static_pointer_cast<T>(spu)`
    - `spt` is a `shared_ptr<T>`, `spu` is a `shared_ptr<U>`
    - `U*` must be convertible into `T*` using `static_cast`
  - `spt = dynamic_pointer_cast<T>(spu)`
    - same as before but using `dynamic_cast`
    - if the cast fails, return an empty shared pointer for `spt`
  - `spt = const_pointer_cast<T>(spu)`
    - same as before but using `const_cast`

TR1 Smart Pointers
Circular Data Structures and Shared Pointers

If there are no other references to these objects there is no way to delete them ⇒ **Memory Leak**



TR1 Smart Pointers
Shared Pointer Observers: `weak_ptr` (1)

- **A weak pointer is an *observer* of a shared pointer**
  - When the shared pointer releases its resource, it sets the observing weak pointer(s) to null

  Thus a weak pointer never contains a dangling pointer
  - A weak pointer does not interfere in any way with the reference count
- **It is impossible to access to the resource directly through a weak pointer**
  - The weak pointer must first be transformed into a shared pointer
- **Use of weak pointers**
  - Break cyclic dependencies
  - Observe a share resource without the responsibility of ownership
  - Avoid dangling pointers...

TR1 Smart Pointers
Shared Pointer Observers: `weak_ptr` (2)

- **Weak pointer operations**
  - Weak pointers are copiable
  - Weak pointers are transformable to and from shared pointers
  - A `weak_ptr<U>` is implicitly convertible into a `weak_ptr<T>` provided that `U*` is implicitly convertible into `T*`
  - The `get()`, `swap()`, `reset()` operations are similar, *mutatis mutandis*, to their counterparts in `shared_ptr`
  - There are ***no*** dereferencing operators (such as `operator*` or `operator->`) for `weak_ptr`

TR1 Smart Pointers
Shared Pointer Observers: `weak_ptr` (3)

- **Obtaining a `weak_ptr` from a `shared_ptr`**
  - Use the constructor or assignement operator

```
shared_ptr<A> pa(new A());
weak_ptr<A> wp = pa; // constructor not explicit
```

  - Since the constructor is not explicit, the corresponding conversion is implicit
- **Verifying that the observed `shared_ptr` is still owning a resource**
  - The expired operation

```
if (wp.expired()) ... // no resource owned
```


TR1 Smart Pointers
Shared Pointer Observers: `weak_ptr` (4)

- **Obtaining a `shared_ptr` from a `weak_ptr`**
  - Use the constructor or assignement operator

```
weak_ptr<A> wp;
shared_ptr<A> sp(wp); // constructor is explicit
sp = wp;  // assignment
```

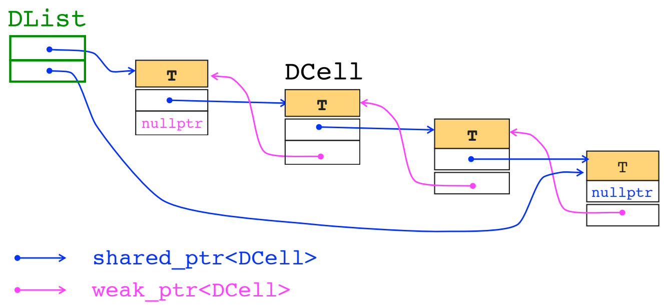
  - Throws bad_weak_ptr if wp is expired
  - Use weak_ptr operation lock()

```
weak_ptr<A> wp;
shared_ptr<A> sp = wp.lock();
```

  - No exception is thrown if `wp` is expired
  - Instead return an ***empty*** shared pointer (thus owning nothing)

TR1 Smart Pointers
Shared Pointer Observers: `weak_ptr` (5)

- **Example of `weak_ptr`: a doubly linked list (1)**



TR1 Smart Pointers
Shared Pointer Observers: `weak_ptr` (6)

- **Example of `weak_ptr`: a doubly linked list (1)**

```
template <typename T> class DList {
public:
    struct DCell  {
        T _t;
        shared_ptr<DCell> _next;
        weak_ptr<DCell> _prev;
        DCell(const T& t) : _t(t) {}
        DCell() {}
        ~DCell() { cout << "DCell destructor\n" };
    };
private:
    shared_ptr<DCell> _head;
    shared_ptr<DCell> _tail;
public:
    shared_ptr<DCell> append(const T& t);
    shared_ptr<DCell> insert_before(shared_ptr<DCell> where,
                                    const T& t) ;
};
```


TR1 Smart Pointers
Shared Pointer Observers: `weak_ptr` (7)

- **Example of `weak_ptr`: a doubly linked list (2)**

```
template <typename T>
shared_ptr<DList<T>::DCell>
DList<T>::append(const T& t) {
    shared_ptr<DCell> newcell(new DCell(t));
    if (not _head)
        _head = _tail = newcell;
    else {
        _tail->_next = newcell;
        newcell->_prev = _tail; // implicit conversion
        _tail = newcell;
    }
    return newcell;
}
```


TR1 Smart Pointers
Shared Pointer Observers: `weak_ptr` (8)

- **Example of `weak_ptr`: a doubly linked list (3)**

```
template <typename T>
shared_ptr<DList<T>::DCell>
DList<T>::insert_before(shared_ptr<DCell> where,
                        const T& t) {
    if (not where)
        return append(t);
    shared_ptr<DCell> newcell(new DCell(t));
    newcell->_prev = where->_prev;
    newcell->_next = where;
    // where->_prev->_next = newcell; // ➔ DOES NOT COMPILE
    shared_ptr<DCell> prev = where->_prev.lock();
    if (prev)
        prev->_next = newcell;
    else
        _head = newcell;
    where->_prev = newcell;
    return newcell;
}
```


TR1 Smart Pointers
`enable_shared_from_this` (1)

- **The problem**

```
struct A {
    ~A() { cout << "A destructor\n"; }
    shared_ptr<A> f() {
        return shared_ptr<A>(this);
    }
};
```

- What if the `A` object is already owned by a shared pointer?

```
int main() {
    shared_ptr<A> pa1(new A());
    shared_ptr<A> pa2(pa1->f());
}
```

Two calls to `A` destructor for the same object

- At first, the `A` object is owned by `pa1`
- When calling `pa1->f()` a fresh shared pointer is returned, with its own reference count; thus the `A` object is now owned by two completely different shared pointers
- Thus it is deleted twice!

TR1 Smart Pointers enable_shared_from_this (2)

- **The solution**

```
struct A : std::enable_shared_from_this<A> {
    ~A() { cout << "A destructor\n"; }
    shared_ptr<A> f() {
        return this->shared_from_this();
    }
};

int main() {
    shared_ptr<A> pa1(new A());
    shared_ptr<A> pa2(pa1->f());
}
```

Only one call to A destructor

  - Base class contains an observer (a `weak_ptr`) of the shared pointer on the `A` object
  - When calling `pa1->f()`, if there exists already a shared pointer owning the `A` object, `shared_from_this()` returns a copy of this shared pointer
  - Otherwise `shared_from_this()` throws `bad_weak_ptr`

Smart Pointers and Inheritance Conversion (1)

- **It is possible to construct a *`XXX`*`_ptr<T>` from an *`XXX`*`_ptr<U>` provided that `U*` is implicitly convertible into `T*`**
- **This is the case when `U` derives from `T`**
- **This is implemented as a constructor template in the smart pointer classes**

```
template <typename T>
template <typename U>
shared_ptr<T>::shared_ptr(
            const shared_ptr<U>& spu);
```


Smart Pointers and Inheritance Conversion (2)

```
class A { . . . }; // destructor not virtual
class B : public A { . . . };
XXX_ptr<A> pa(new B());
```

- **Which destructor is called?**
  - `boost::scoped_ptr` and `std::unique_ptr` calls `~A()`
  - `std::shared_ptr` calls directly `~B()` and accepts `~A()` to be protected
  - Identical behavior for the deleter...

Smart Pointer and Inheritance Conversion Protected Destructor Idiom for shared_ptr (1)

```
class A {
    // . . .
public:
    ~A();
};

class B : public A {
    // . . .
};

shared_ptr<A> pa1(new A());
delete pa1->get(); // not a good idea, but allowed
A a = *pa1;  // crash or incorrect behavior likely
```

Smart Pointer and Inheritance Conversion
Protected Destructor Idiom for `shared_ptr` (2)

```
class A {
    // . . .
protected:
    ~A();
};

class B : public A {
    // . . .
public:
    ~B();
};

shared_ptr<A> pa1(new A());
delete pa1->get(); // does not compile any more

shared_ptr<A> pa2(new B());
        // Destruction of pa2 OK: call directly B()
```


Pros and Cons of Smart Pointers

- **Pros**
  - Safe deallocation, especially for `shared_ptr`
    - No memory leak, no crash due to spurious deletions
  - Inheritance and virtual functions still operational
  - Easy to use: simply replace `A*` with `shared_ptr<A>`
- **Cons**
  - Problem with circular structures (`weak_ptr`)
  - Strange copy: ownership transfer or move semantics
  - Size penalty: shared and weak twice the size of a regular pointer
  - Speed penalty for copy operations?

Pros and Cons of Smart Pointers
Size of smart pointers

	`sizeof`	factor
regular pointer (`T*`)	8	×1
`auto_ptr`	8	×1
`unique_ptr`	8	×1
`shared_ptr`	16	×2
`weak_ptr`	16	×2
Intel Xeon (64 bits)		

Pros and Cons of Smart Pointers
Tips and Traps

- **Avoid `auto_ptr`**
- **If copy or sharing is not needed, use `scoped_ptr` or `unique_ptr`**
- **If sharing is needed or in case of doubt, use `shared_ptr`**
  - but take care of circular pointer chains (`weak_ptr`)
- **Never mix `smart_ptr` and regular C pointers**
  - A rule of thumb: if you use `shared_ptr`, you should **never** declare a regular pointer and you should restrict the use of `share_ptr::get()` to pass a regular pointer to a **legacy C** function (e. g., system programming)
- **Shared pointer are not guaranteed thread safe in the C++03 standard**
  - but they are some thread safe implementations (e. g., **g++**)
  - however, they do not solve the problem of concurrent updates of the pointed object: mutexes are still required for this

Advanced C++ Libraries and Introduction to Template Metaprogramming

Part 4

Type Traits and High Order Programming

Consulting and Manipulating Types

- **Boost and TR1 `type_traits`**
- **Control of template instantiation: `std::enable_if`**
- **High order programming**
  - Boost and TR1 `bind` adaptor
  - Boost and TR1 `function`
  - C++11 lambda expressions and closures

Boost and TR1 Type Traits (1)

- **Boost vs TR1/C++11**
  - Identical functionality...
    - ... but notational differences
    - Do not use both simultaneously!
- **Set of template classes (in fact `struct`) to consult or even transform type properties at compile time**

- **Exemple**

```
// Using C++11

#include <type_traits>
using namespace std;

template <typename T>
class A {
  static_assert(
    not is_void<T>::value,
    "cannot instantiate A");

  T *_pt;
  . . .
};
```


Boost and TR1 Type Traits (2)

- **Convention for type traits classes**

```
template <typename T>
struct property {
  static const Tval value = val;
  typedef Ttype type;
};

if (property<MyType>::value) . . .
typedef property<MyType>::type MyType2;
```

The type(s) to operate on (there can be several of them)

The property or transformation

The result is a value (`Tval` is usually `bool` or `int`)

The result is a type

Boost and TR1 Type Traits
Integer to Type (1)

```
template <typename T, T val>
struct integral_constant {
  static const T value = val;
  typedef T value_type;
  typedef integral_constant<T, val> type;
};
```

- Type `T` must be integral

```
typedef integral_constant<bool, true> true_type;
typedef integral_constant<bool, false> false_type;
```

- **All type predicates further (properties of the forms `is_XXX`, `has_XXX`) derive either from `true_type` of `false_type`**

Boost and TR1 Type Traits
Integer to Type (2)

- **Exemple of use**

```
template <typename T>
struct A {
  T _t;
  void save() {
    if (is_pointer<T>::value)
      _t->save();
    else
      _t.save();
  }
};
```

- **Check at run-time!**
- **Anyhow, it does not compile!**
  - Compiler requires that the 2 branches of `if` be compilable

- **Dispatching at compile time**

```
template <typename T>
struct A {
  T _t;
  void save(true_type){_t->save();}
  void save(false_type){_t.save();}

  void save() {
    save(
      integral_constant<
          bool,
          is_pointer<T>::value>());
  }
};
```


Boost and TR1 Type Traits
Property Query

- **Primary categories (`bool` value)**
  - `is_void<T>`
  - `is_integral<T>`, `is_floating_point<T>`
  - `is_array<T>`
  - `is_pointer<T>`, `is_reference<T>`
  - `is_member_object_pointer<T>`, `is_member_function_pointer<T>`
  - `is_enum<T>`, `is_union<T>`, `is_class<T>`
  - `is_function<T>`
- **Composite categories (`bool` value)**
  - `is_arithmetic<T>`, `is_fundamental<T>`
  - `is_object<T>`, `is_scalar<T>`
  - `is_compound<T>`
  - `is_member_pointer<T>`
- **Type properties (`bool` value)**
  - `is_const<T>`, `is_volatile<T>`
  - `is_signed<T>`, `is_unsigned<T>`
  - `is_pod<T>`, `is_empty<T>`
  - `is_polymorphic<T>`, `is_abstract<T>`
  - `is_constructible<T>` (trivially, nothrow, copy...)
  - `is_copy_assignable<T>` (trivially, nothrow, copy...)
  - `is_assignable<T, U>`
  - `has_virtual_destructor<T>`
- **Type properties (`unsigned` value)**
  - `alignment_of<T>`
  - `rank<T>` (number array dimensions)
  - `extend<T, I = 0>` (upper bound of the `I`th dimension)

Boost and TR1 Type Traits
Relations and Transformations

- **Relations (`bool` value)**
  - `is_same<T1, T2>`
  - `is_base_of<Base, Derived>`
  - `is_convertible<From, To>`
- **Transformation (`type`)**
  - `remove_const<T>`, `remove_volatile<T>`, `remove_cv<T>`
  - `add_const<T>`, `add_volatile<T>`, `add_cv<T>`
  - `remove_reference<T>`, `add_reference<T>`
  - `remove_pointer<T>`, `add_pointer<T>`
  - `remove_extent<T>`, `remove_all_extents<T>`
  - `aligned_storage<Lenght, Align>`
- etc.

Boost and TR1 Type Traits
Exemple: Call Parameter (a.k.a. Call Traits)

```
template <typename T>
struct A {
  unsigned f(T t) {
    . . .
  }
};
```

- If T is a scalar, passing by value is good, but if T's are big objects passing by reference (to a constant) is better

```
template <typename T>
struct A {
  unsigned f(
    typename call_param<T>::type t)
  {
    . . .
  }
};
```

- This is **not** a complete solution: see `boost::call_traits`

```
template <typename T, bool isScalar>
struct call_param_helper { };

template <typename T>
struct call_param_helper<T, true> {
  typedef T type;
};

template <typename T>
struct call_param_helper<T, false> {
  typedef const T& type;
};

template <typename T>
struct call_param {
  typedef typename
    call_param_helper<
      T,
      is_scalar<T>::value
    >::type type;
};
```


Control of Template Instantiation: `std::enable_if` (1)

```
template <typename Iter>
typename Iter::value_type
sum(Iter first, Iter last) {
    typedef typename Iter::value_type T;
    T s = T();
    for (Iter it = first; it != last; ++it)
       s += *it;
    return s;
}
```

- **Suppose that we wish to use this algorithm only when `T` is a numeric type**
- **How to remove `sum()` from candidate functions when `T` is not numeric?**
  - Static assertions would provoke compilation errors
  - Conditional compilation does not work
- **But we can provoke a substitution failure... SFINAE (which is not an error...)**

Control of Template Instantiation: `std::enable_if` (2)

- **`enable_if` makes it possible to control overloading resolution**
  - **Beware:** `boost::enable_if` and `std::enable_if` (C++11) are slightly different: here we use `std::enable_if`
- **The `enable_if` templates from C++11**

```
template <bool B, typename T = void>
struct enable_if { typedef T type; };

template <typename T>
struct enable_if<false> { };
```

  - The expression `enable_if<B, T>::type` yields a valid type (`T`) if `B` is true and is invalid otherwise

Control of Template Instantiation: `std::enable_if` (3)

```
template <typename Iter>
typename std::enable_if<
  is_arithmetic<typename Iter::value_type>::value,
  typename Iter::value_type
>::type
sum(Iter first, Iter last) {
  typedef typename Iter::value_type T;
  T s = T();
  for (Iter it = first; it != last; ++it)
     s += *it;
  return s;
}
```

- Now, `sum()` is a valid candidate if and only if `T` is an arithmetic type...

Control of Template Instantiation: `std::enable_if` (5)

- **Removing a candidate from the overloading set (1)**
  - Trying to print a whole container?

```
template <typename Container>
ostream& operator<<(ostream& os, const Container& cont)
{
     typename Container::const_iterator Iter;
     for (Iter it = cont.begin(); it != cont.end(); ++it)
         os << *it << ' ';
     return os;
}
```

- **This does not work!**
  - This function is always candidate, since `Container` can be any type

hence possible compile-time errors

  - Some containers already have `operator<<` (e.g. `string`), hence ambiguity

Control of Template Instantiation: `std::enable_if` (6)

- **Removing a candidate from the overloading set (2)**

```
template <typename Container>
typename std::enable_if<
     not is_same<Container, string>::value,
     ostream&
>::type
operator<<(ostream& os, const Container& cont)
{
     // Same as before...
}
```

  - This removes the function from the overload set when the container is `string`, allowing to correctly lookup string `std::operator<<`
  - However this function is still candidate for all types (except `string`), hence possible compile-time errors

We need to remove the function also when `Container` is not a container type: e.g. it has no type member `value_type` or `const_iterator`

Control of Template Instantiation: `std::enable_if` (7)

- **Introspection for a member type (1)**

```
template<typename C>
struct has_type_value_type
{
    struct _yes {char c;};
    struct _no {_yes a[2];};

    template <typename T>
    static _yes _dummy(typename T::value_type*);

    template <typename >
    static _no _dummy(...);

    static const bool value = sizeof(_dummy<C>(0)) == sizeof(_yes);
};
```

  - **The `sizeof` trick!** Nothing is evaluated (but types and purely type dependent operations such as overloading) within `sizeof`

Hence function `_dummy` needs not be defined

  - Note that constant 0 is convertible into a pointer to member

Control of Template Instantiation: `std::enable_if` (8)

- **Introspection for a member type (2)**

```
#define DEF_HAS_MEMBER_TYPE(TYPE) \
template<typename C>  \
struct has_type_##TYPE \
{ \
    struct _yes {char c;}; \
    struct _no {_yes a[2];}; \
 \
    template <typename T> \
    static _yes _dummy(typename T::TYPE*); \
 \
    template <typename > \
    static _no _dummy(...); \
 \
    static const bool value = sizeof(_dummy<C>(0)) ==
sizeof(_yes); \
};
```

Control of Template Instantiation: `std::enable_if` (9)

- **Removing a candidate from the overloading set (3)**

```
DEF_HAS_MEMBER_TYPE(value_type); // struct has_type_value_type
DEF_HAS_MEMBER_TYPE(const_iterator); // struct
has_type_const_iterator

template <typename Container>
typename std::enable_if<
   not is_same<Container, string>::value
   and has_type_value_type<Container>::value
   and has_type_const_iterator<Container>::value,
   ostream&
>::type operator<<(ostream& os, const Container& cont)
{
   // Same as before...
}
```

- Now the function appears in the overload set only if type `Container` is not `string` and if it has member types `value_type` and `const_iterator`

High Order Programming

- **STL (2003) function objets and function adaptors**
  - `mem_fun`, `mem_fun_ref`, `ptr_fun`, `bind1st`, `bind2nd`...
- **Boost and TR1 function adaptors**
  - `bind`, `mem_fn`
  - Reference wrappers: `ref`, `cref`
  - Direct manipulation of function objects: `function`
- **C++11 lambda expressions**

High Order Programming STL Function Objects and Adaptors (1)

- **Function objects and functors in C++ 2003**
  - A *function object* is an instance of a *functor*, i.e. a class defining `operator()`
  - Often derived from `unary_function<Param, Return>` or `binary_function<Param1, Param2, Return>`

```
template <typename T>
struct printer : unary_function<const T&, void> {
    void operator()(const T& t) {
        cout << t << ' ';
    }
};
. . .
list<int> l;
. . .
for_each(l.begin(), l.end(), printer<int>());
```


High Order Programming STL Function Objects and Adaptors (2)

- **Function adaptors (functionals)**
  - Creation of function objects
  - Parameter binding: `bind1st`, `bin2nd`

```
list<int>::iterator it =
  find_if(l.begin(), l.end(), bind2nd(greater<int>(), 5));
```

  - Transformation of regular functions or member functions into function objects

```
struct Figure {
     void draw() const;
     int rotate(int angle);
};

dequeue<Figure *> dq
for_each(dq.begin(), dq.end(), mem_fun(&Figure::draw));

list<int>li;
transform(dq.begin(), dq.end(), back_inserter(li),
          bind2nd(mem_fun(&Figure::rotate), 3.141592));
```

High Order Programming
STL Function Objects and Adaptors (3)

- **Drawbacks of STL (2003) function adaptors**
  - Distinction between different natures of functions

regular functions
member functions
well-formed function objects

  - Functions must have no more than 2 parameters
  - Difficult to compose functions
  - Terrible syntax

```
bind2nd(mem_fun(&Figure::rotate), 3.141592));
```

  - Possible problems with parameters passed by reference...
  - Problem with containers of smart pointers

High Order Programming
Boost and TR1 `bind` Adaptor (1)

```
bind<Return>(f, p1, p2, …, pn)
```

- `<Return>` is optional if the compiler can deduce it
  - if present, `Return` designates the return type of the function object
- `f` may be a (pointer to) a regular function or a function object with `n` parameters
- `f` may be a (pointer to an) instance member function with `n-1` parameters (not accounting for `this` which will become the first parameter of the function object)
- The parameters p_i may be
  - either an expression which will be bound to the corresponding parameters of `f`
  - or a ***placeholder*** such as _1, _2, _3... which corresponds to a *free variable*, thus a parameter of the produced function object
- The **function object** produced will have
- as many parameters as the number of different placeholders used: they must be used in order _1, _2, ...
- its parameters passed **by reference** to a variable: thus the effective parameter cannot be a literal value nor an expression yielding a value (no longer true in C++11)

High Order Programming
Boost and TR1 `bind` Adaptor (2)

- **Examples of function objects (φ) created by `bind`**

```
int f(int a, int b) { return a - b; }

bind(f, _1, 3)     ➔   φ(x)    = f(x, 3)
bind(f, 4, 3)      ➔   φ()     = f(4, 3)
bind(f, _1, _2)    ➔   φ(x, y) = f(x, y)
bind(f, _1, _1)    ➔   φ(x)    = f(x, x)
bind(f, _2, _1)    ➔   φ(x, y) = f(y, x)

int n = 4, m = 3;
bind(f, _1, 3)(n)        == 1
bind(f, _1, _2)(n, m)    == 1
bind(f, _1, _1)(n)       == 0
bind(f, _2, _1)(n, m)    == -1
bind(f, _1, _1)(3)       ➔ does not compile in C++03
bind(f, _1, _1)(n + 1)   ➔ does not compile in C++03
```


High Order Programming
Boost and TR1 `bind` Adaptor (3)

- **Usage of `bind`**

```
struct Figure {
    void draw() const;
    int rotate(double angle);
};

dequeue<Figure *> dq;
for_each(dq.begin(), dq.end(), bind(&Figure::draw, _1));

list<int> li;
transform(dq.begin(), dq.end(), back_inserter(li),
          bind(&Figure::rotate, _1, 3.141592));
```

High Order Programming
Boost and TR1 `bind` Adaptor (4)

- **Function composition with `bind`**

```
struct Figure {
    void draw() const;
    int rotate(double angle);
    unsigned diameter() const;
};

deque<Figure *> dq;
sort(dq.begin(), dq.end(),
     bind(less<unsigned>(),
          bind(&Figure::diameter, _1),
          bind(&Figure::diameter, _2)));
```


High Order Programming
Boost and TR1 `bind` Adaptor (5)

- **Binding data members**

```
map<int, string> m;
typedef map<int, string>::value_type pair_type;
void print_string(const string& s);

for_each(m.begin(), m.end(),
         bind(&print_string,
              bind<string>(&pair_type::second, _1)));
```

  - Binding a data member is like using an accessor

High Order Programming
Boost and TR1 `bind` Adaptor (6)

- **Parameter of `bind`**
  - The parameters to `bind` are ***copied*** into the function object
  - If not desired, use *reference wrappers* `ref` and `cref`

```
string add_suffix(const string& s, int& suffix) {
    ++suffix;
    return s + boost::lexical_cast<string>(suffix);
}

int suffix_list(list<string>& ls) {
    int suffix = 0;
    transform(ls.begin(), ls.end(), ls.begin(),
              bind(&add_suffix, _1, ref(suffix)));
    return suffix;
}
```

  - `ref(v)` encapsulates a reference to a variable
    - `ref` objects are ***copiable***, whereas ordinary references are not
  - If a reference to a constant is needed, uses `cref(v)`

High Order Programming
Boost and TR1 `bind` Adaptor (7)

- **Advantages of `bind`**
  - Function objects with up to 9 parameters
  - Possibility of argument reordering
  - Compatible with smart pointers such as `shared_ptr` (`mem_fun` is not)
  - Compatible with reference wrappers (`ref` and `cref`)
  - Possibility to bind data members (a sort of getter)
  - Possibility of function object composition
- **Beware!**
  - In TR1 (before C++11), the placeholders are in `std::tr1::placeholders`
  - In C++11, they will be in `std::placeholders`
  - In Boost they are in `::`, the global namespace

High Order Programming
Boost and TR1 `bind` Adaptor (8)

- **Compatibility of `bind` with previous STL**
  - STL 2003 functors defines nested types for the result type and the parameter type(s)
  - The STL 2003 functionals expect and use these nested types

```
list<char *> lcstr;
int c = count_if(lcstr.begin(), lcstr.end(),
    not1(bind2nd(ptr_fun(strcmp), "hello")));
```

  - bind does not define these nested types

```
int c = count_if(lcstr.begin(), lcstr.end(),
    not1(bind(strcmp, _1, "hello")));
error: no type named 'argument_type' . . .
```


High Order Programming
Boost and TR1 `function` (1)

- **Problem with `bind`**
  - Creating and storing a function object to use it later?

```
void foo(int a, int b) { . . . }
??? fobj = bind(foo, _1, 3); // type unknown
fobj(5); // ???
```

    - The type is determined with respect to the ***context of call***
- **Use Boost or TR1 `function`**

```
function<void(int)> fobj = bind(foo, _1, 3);
fobj(5);
```

    - Any sort of callable can be converted into an instance of function<> (with the suitable signature)
    - A powerful replacement for pointer to functions...

High Order Programming
Boost and TR1 `function` (2)

- **Construction of function objects using function**

```
function<int(int, int)> f;
```

    - The default constructor yields an empty function object

```
if (f.empty()) ... // true
if (not f) ...     // true
f(3, 3);    // throw bad_function_call
```

  - The function object can be initialized with
    - a regular function or a function object of the same signature
    - a reference wrapper to a function object of the same signature
    - a member function the first parameter of which must be the class of this member
  - The function objects created with function are copiable
  - Up to 10 parameters (library configuration)
  - Some compilers do not accept the above syntax for the signature (g++ does)
    - Alternative forms:

```
function1<void, int)> f1; function2<void, int, int)> f2; ...
```


High Order Programming
Boost and TR1 `function` (3)

- **Examples of construction of function objects using `function`**

```
int myplus(int, int);
function<int(int, int)> f1 = &myplus;
function<int(int, int)> f2 = std::plus<int>();
int a = f1(3, 4);
int b = f2(a, 5);
f1 = f2;

struct Figure {
    double rotate(double);
    // ...
};
function<double(Figure, double)> f3 = &Figure::rotate;
double x = f3(Figure(), 3.5);

function<double(Figure*, double)> f4 = &Figure::rotate;
x = f4(new Figure(), 3.5);
```

High Order Programming
Boost and TR1 `function` (4)

- **Function objects with state**
  - As usual, function objects may have internal attributes
  - Thus they accumulate information each time they are called
- **However always remember that function objects are copied by value**

```
struct Accumulate {
    int _total;
    Accumulate() : _total(0) {}
    int operator()(int a) {
        _total += a;
        return _total;
    }
};

Accumulate acc;
function<int(int)> facc1 = acc;
function<int(int)> facc2 = acc;
cout << facc1(10) << ' ';
cout << facc2(10) << endl;  // 10 10
cout << acc._total << endl; // 0
```


High Order Programming
Boost and TR1 `function` (4bis)

- **Function objects with state**
  - As usual, function object may have internal attributes
  - Thus they accumulate information each time they are called
- **However always remember that function objects are copied by value**

```
struct Accumulate {
    int _total;
    Accumulate() : _total(0) {}
    int operator()(int a) {
        _total += a;
        return _total;
    }
};

Accumulate acc;
function<int(int)> facc1 = ref(acc); // form a reference
function<int(int)> facc2 = ref(acc); // form a reference
cout << facc1(10) << ' ';
cout << facc2(10) << endl;  // 10 20
cout << acc._total << endl; // 20
```


High Order Programming
Boost and TR1 `function` (5)

- **`function` and `bind`**
  - These two functions are compatible
    - One can create a function<...> as the result of bind

    `function<int(int)> f1 = bind(plus<int>(), _1, 3);`

    - One can also bind the arguments of a function<...>

    `function<int()> f2 = bind(f1, 5);`

High Order Programming
Boost and TR1 `function` (6)

```
struct Window {
    int _x, _y;

    Window() : _x(0), _y(0) {}
    void up();
    void down();
    void left();
    void right();
};

int main()
{
    typedef function<void()> Command;
    Window w;
    map<string, Command> cmds = {    // C++11 initialization syntax
        {"up",    bind(&Window::up,    ref(w))},
        {"down",  bind(&Window::down,  ref(w))},
        {"left",  bind(&Window::left,  ref(w))},
        {"right", bind(&Window::right, ref(w))},
    };

    string cmd;
    while (cin >> cmd)
        cmds.at(cmd)();     // C++11: throw exception 'out_of_range' if cmd invalid
}
```

High Order Programming
Boost and TR1 `function` (7)

- **Advantages of `function`**
  - Replacement of pointers to functions
  - Compatible with (nearly) all ways of representing something like a function in C++
  - Compatible with STL 2003 for 1 and 2 argument functions
  - Function objects may have state
- **Drawbacks**
  - Be careful with copying function objects
  - Cost: 4 times bigger than a regular pointer to function
  - Does not solve the overloading problem

```
int g(int i);
double g(double x);
function<int(int)> fg = &g; // does not compile
function<int(int)> fg = static_cast<int(*)(int)>(&g);//!!
```


High Order Programming
C++11 Lambda Expressions and Closures (1)

- **Problems with `bind`**
  - The syntax of `bind` is improved but still ugly
  - It is still necessary to define dedicated function objects (at global or namespace scope)

```
struct printer {
    template <typename T>
    void operator()(const T& t) {cout << t << ' ';}
};
list<double> lx;
for_each(lx.begin(), lx.end(), printer());
```

- **Two different and incompatible implementations of lambda**
  - `boost::lambda`, a library implementation (obsolete)
  - *lambda expressions* and *closures* as part of core C++11

High Order Programming
C++11 Lambda Expressions and Closures (2)

- **Example of C++11 lambda expression**

```
list<double> lx;
for_each(lx.begin(), lx.end(),
         [] (double x) { cout << x << ' '; });
```

- **Anatomy of a lambda expression**

```
[...] (P1 p1, ..., Pn pn) -> T { . . . }
```

Capture of "more global" variables | Parameter list | Return type | Body

Defines a function `T anonymous(P1 p1, ..., Pn pn)`

Part of syntax in Magenta is optional

High Order Programming
C++11 Lambda Expressions and Closures (3)

- **Return type**
  - Optional if the compiler can deduce it unambiguously
- **Capture list**
  - Make variables in local scope available within the lambda body
  - Several forms:

`[]`	do not capture anything
`[=]`	capture everything, by value
`[&]`	capture everything, by reference
`[x, y]`	capture only `x`, `y` by value
`[&x, &y]`	capture only `x`, `y` by reference
`[&x, y]`	capture `x` by reference, `y` by value, and nothing else...

High Order Programming C++11 Lambda Expressions and Closures (4)

- **Capture list example**

```
int suffix_list(list<string>& ls) {
    int suffix = 0;
    transform(ls.begin(), ls.end(), ls.begin(),
              [&suffix] (const string& s) {
                  ++suffix;
                  return s + boost::lexical_cast<string>(suffix);
              } );
    return suffix;
}
```

- **Note that `this` must be captured to be able to access class members**

```
struct A {
    int _a;
    A() : _a(0) {}
    void f() {
        cout << [=]() {return ++_a;} () << endl;
    }
};
```


Evaluation of High Order Programming in TR1 and C++11

- **`bind`, and `function` are a real improvement over STL 2003 constructs**
  - Respect the STL philosophy
  - Simple to use
  - Powerful (e.g., function composition)
- **However,**
  - delicate incompatibilities between `bind` and STL 03 function objects
  - still problems with overloaded functions
- **C++11 lambdas are a totally new construct**
  - Powerful, simple enough
  - The function is defined where it is needed
    - Possibility of local function
  - Compatibility with `bind`/`function`

Advanced C++ Libraries and Introduction to Template Metaprogramming

Part 5

Containers and Algorithms

Containers and Algorithms

- **TR1 containers (also in Boost)**
  - `tuple`
  - `array`
  - Unordered associative containers
- **Boost “polymorphic” containers**
  - `any`, `variant`
  - pointer containers
- **Other Boost containers**
  - multi-arrays, multi-index, bidirectional maps
  - property maps
  - intrusive containers

TR1 Containers
Tuples (1)

- **Extension of the `pair<T,U>` structure**
- **`tuple<T₁, T₂, …, Tₙ>`**
  - T_i are types (possibly references)
  - $n \geq 0$ (guaranteed maximum $n \leq 10$)

  no real maximum if *variadic templates* supported
- **Tuple properties**
  - Copiable, assignable, provided T_i are
  - Comparable (==, <, …), provided T_i are
  - `tuple<T,U>` interoperable with `pair<T,U>`

TR1 Containers
Tuples (2)

- **Examples of tuples**

```
typedef tuple<int, double> Doublet;
Doublet t1(3, 2.5);
Doublet t2 = t1; // Copy constructor

typedef tuple<int&, double> Tref;
int i = 0;
Tref tr1(i, 3.5); // OK
tr1 = t2;  // OK
assert(i == 3);
```

- The first element of `tr1` is a reference to `i`

```
Tref tr2(3, 3.5); // NO!
```

- 3 cannot be bound to a `int&`

TR1 Containers
Tuples (3)

- **Tuple accessors**
  - `tuple_size<Tuple>::value`
    - Number of elements in the Tuple type

```
typedef tuple<int, string, double> Triplet;
static_assert(tuple_size<Triplet>::value == 3, "");
```

  - `tuple_element<I, Tuple>::type`
    - Type of the element of index I in the Tuple type

```
tuple_element<1, Triplet>::type s; // s is a string
```

  - `get<I>(t)`
    - Return a reference (possibly const) onto the element of index I in the Tuple t

```
Triplet t; // all zeroes of their type
get<2>(t) = 3.5; // t == (0, "", 3.5)
```


TR1 Containers
Tuples (4)

- **Tuple convenience functions**
  - `make_tuple(t1, t2, …, tn)`
    - make a `tuple<T1, T2, …, Tn>` where `Ti` is the type of `ti`

```
tuple<int, double, string> t = make_tuple(3, 4.5, "hello");
```

  - `tie(t1, t2, …, tn)`
    - equivalent to `make_tuple(ref(t1), ref(t2), …, ref(tn))` where `ref` is the C++ (non const) *reference wrapper*
    - `ti` must be (non const) references
    - Usually used on the left of an assignment

```
int i;
string s;
tie(i, s) = make_tuple(3, "hello"); // i == 3, s == "hello"
```

    - Special marker ignore prevents copy for the corresponding element

```
tie(i, ignore) = make_tuple(3, "bye"); // string unchanged
```

TR1 Containers
Tuples (5)

- **Defining a function `print_tuple` is easy with some template metaprogramming**

```
template <typename Tuple, int I>
struct print_helper {
    static void print(ostream& os, const Tuple& t) {
        print_helper<Tuple, I - 1>::print(os, t);
        os  << ", " << get<I>(t);
    }
};
template <typename Tuple>
struct print_helper<Tuple, 0> {
    static void print(ostream& os, const Tuple& t) {
        os << get<0>(t);
    }
};
template <typename Tuple>
void print_tuple(ostream& os, const Tuple& t) {
      os << "( ";
     if (tuple_size<Tuple>::value > 0)
          print_helper<Tuple, tuple_size<Tuple>::value - 1>::print(os, t);
      os << " )";
}
```


TR1 Containers
Tuples (6)

- **Defining stream `operator<<` for tuples ?**

```
template <typename Tuple>
ostream& operator<<(ostream& os, const Tuple& t) {
    print_tuple(os, t);
 }
```

  - This does not work: it creates ambiguities

```
template <typename Tuple>
typename std::enable_if<
     tuple_size<Tuple>::value >= 0,
     ostream&
>::type operator<<(ostream& os, const Tuple& t) {
    print_tuple(os, t);
}
```


TR1 Containers
Tuples: Interoperability with pairs

- **Using pairs as tuples**

```
pair<int, string> p(10);
get<1>(p) = "hello";

int i;
string s;
tie(i, s) = make_pair(12, "bye");
assert(tuple_size<pair<int, string>>::value == 2);
```

- **Using tuples as pairs**

```
tuple<int, string> t(make_pair(12, "bye"));
```


TR1 Containers
Simple Fixed Arrays: `array`

- **Simple array class**

```
array<T, N> a1;
```

  - Array of `T` elements with a fixed size `N`
- **As efficient as ordinary C arrays, but carries its dimension**

```
unsigned n = a1.size(); // n == N
```

- **All properties of `std::vector`**
  - Except it does not grow or shrink (no `push_back`, `pop_front`, `insert`...)
- **Easy to initialize**

```
array<int, 4> a2 = {1, 2, 3, 4}; // C++11? not gcc
array<int, 4> a2 = {{1, 2, 3, 4}}; // C++03
```

TR1 Containers
Unordered Associative Containers

- **`unordered_map<K, T>`, `unordered_multimap<K,T>`**
- **`unordered_set<K>`, `unordered_multiset<K>`**
  - Fast search and retrieval (average O(1), worst case linear)
  - Does not require an order relation over `K`
  - Use hash coding
    - Special `hash<T>` functor with predefined specializations for usual types (in `<functional>`)
  - Same interface as the corresponding ordered associative collections
    - plus some extra functions or parameters to handle hashing configuration

Boost "Polymorphic" Containers

- **Objects of different types in the same container**
- **`boost::variant`**
  - Discriminated union of a fixed and finite set of types
  - Type safe storage and retrieval
- **`boost::any`**
  - Discriminated union of an unbounded set of types
  - Typesafe storage and retrieval
- **Pointer containers**
  - Alternative to using containers of `shared_ptr`

Boost "Polymorphic" Containers
`boost::variant` (1)

- **C and C++ unions are not discriminated**

```
union Real_Int {double x; int i;}
Real_Int u;
u.x = 3.141592;
int a = u.i; // a == -57999238 ???
```

- **C++ unions cannot contains members with constructors**

```
union {int i; string s;}; // NO
```

- **Boost variant class template**

```
variant<double, int> v(3.141592);
int a = get<int>(v); // throw boost::bad_get
int *pa = get<int>(&v); // pa is null
```


Boost "Polymorphic" Containers
`boost::variant` (2)

- **Properties of boost::variant**
  - Variants are copiable (if their elements are)
  - Variants are comparable (if their elements are)
  - Implicit conversions are possible only if unambiguous
  - `which()`
    - return the index of the type currently occupying the variant
  - `type()`
    - return the type_info of the type currently occupying the variant

```
variant<double, int> v(3);
assert(v.which() == 1);
assert(v.type() == typeid(int));
```

Boost "Polymorphic" Containers
`boost::variant` (3)

- **Visitor for boost::variant**

```
struct ostream_visitor : public
static_visitor<void> {
    ostream& _os;
    ostream_visitor(ostream& os) : _os(os) {}

    template <typename T>
    void operator()(T& t) const {
        _os << t;
    }
};
```

  - Note that passing `t` by reference avoids most implicit conversions

```
variant<double, int, char> v('a');
apply_visitor(ostream_visitor(cout), v); // -> 'a'
```


Boost "Polymorphic" Containers
`boost::any` (1)

- **Store a value of an almost arbitrary type**
- **Allow safe storage, retrieval, and copy**
- **A sort of unbounded union**
- **Constraints on the type of value**
  - Copy constructible
    - This one is mandatory
  - Assignable
    - If not assignable, strong exception guarantee may be lost
  - Non-throwing destructor
    - As always!

Boost "Polymorphic" Containers
`boost::any` (2)

```
#include <boost/any.hpp>

class any {
public:
   any();
   any(const any&);
   ~any();

   any& swap(any&);
   any& operator=(const any&);

   template <typename V> any(const V&);  // conversion
   template <typename V> any& operator=(const V&); // conversion

   bool empty() const;
   const type_info& type() const;
};
```


Boost "Polymorphic" Containers
`boost::any` (3)

- **Extracting the current value**

```
any a;
T t = any_cast<T>(a);
```

  - The previous expression throws exception `bad_any_cast` if a does not contain a value of type `T`

```
T *pt = any_cast<T>(&a);
```

  - The previous expression returns 0 if a does not contain a value of type `T`

- **Example**

```
any a;
a = string("hello"); // see next slide
a = 12;
int i = any_cast<int>(a); // OK
string *s = any_cast<string>(&a); // null
```

Boost "Polymorphic" Containers `boost::any` (4)

- **Putting pointers into `any`**
  - `any` is not considered empty when holding a null pointer
  - `any` destructor won't destroy the object pointed to
  - polymorphism is not honored
- **Be careful when putting `char*` into `any`**
  - Put `string` instead
- **By contrast, it is safe to put `shared_ptr` into `any`**

Boost "Polymorphic" Containers Pointer Containers

- **Alternative to using containers of `shared_ptr` when**
  - sharing is not needed, or
  - shared pointer overhead is not acceptable
- **Pointer containers contain heap allocated objects**
  - They take ownership of them, and destroy them when needed
- **Performance optimization**
  - but requires strict ownership

Other Boost Containers (1)

- **Multi-arrays**
  - Arrays with more than 1 dimension
  - Contiguous in memory
- **Multi-index**
  - Allow to index containers with different strategies
- **Bidirectional maps**
  - `bimap<X,Y>`: two opposite `std::maps`
  - Interoperable with `std::map` (`left` and `right` views)

Other Boost Containers (2)

- **Intrusive containers**
  - Store objects themselves, not copies
  - Advantages
    - No memory management
    - Less memory used
    - An object may belong to several containers simultaneously
    - Fast iteration
    - Better exception guarantee
    - Better predictability on insert/erase (no memory...)
  - Drawbacks
    - The objects must already contain some predefined members, e.g., the next and previous members for a doubly linked list
    - No automatic life time management
    - Intrusive containers are non copiable and non assignable
    - Analyzing thread safety is harder with intrusive containers

Other Boost Containers (3)

- **Property maps**
  - A generic representation of (name, value) pairs
- **Circular buffer**
  - STL compliant: same properties as sequences
  - Contiguous memory
  - Fast insertion, removal, and iteration
- **Dynamic bitset**
  - Dynamic extension of `std::bitset`
- **GIL, the Generic Image Library**
- **GRAPH, generic components and algorithms**

Advanced C++ Libraries and Introduction to Template Metaprogramming

Part 6

String Utilities and Regular Expressions

String Utilities and Regular Expressions

- **Miscellaneous Boost libraries**
  - Lexical cast
  - Format
  - String algorithms
  - Tokenizer
- **TR1 and Boost regular expressions (`regex`)**

Miscellaneous Boost Libraries Lexical Cast

- **Synopsis**

```
template <typename Source, typename Target>
Target lexical_cast(const Source& arg);
```

  - Convert `arg` into type `Target` using stream operators
    - `Source` must be *Output Streamable* (`operator<<`)
    - `Target` must be *Input Streamable* (`operator>>`), *Default* and *Copy Constructible*
  - If conversion does not work, throw `bad_lexical_cast`
- **Example**

```
#include <boost/lexical_cast.hpp>
int i = lexical_cast<int>("-123"); // atoi()
string s = lexical_cast<string>(i + 2); // itoa??
```

Miscellaneous Boost Libraries
Format

- **Motivation**
  - Type-safe `printf`-like format operations
  - Much richer than `printf`
    - Works with any (*Output Streamable*) type
    - Possibility of reordering elements
    - More formatting options...
- **Example**

```
#include <boost/format.hpp>
boost::format f("%05d %5.2f %s\n");
float x = 5.3;
string s = "hello";
cout << f % 3 % x % s;
```


Miscellaneous Boost Libraries
String Algorithms

- **Namespace `boost::algorithm`**
- **A lot of supplementary algorithms for strings**
  - Convert strings to upper/lower case
  - Trim strings
  - Search for, replace, or erase sub-strings
  - Split strings, join substrings
  - Iterators on substrings
- **Interoperability with regular expressions**

Miscellaneous Boost Libraries
Tokenizer (1)

- **String tokenization**
  - Splitting a string into substring with respect to character or substrings considered as separators
- **Many ways to do it using Boost**
  - regular expressions token iterator (see further)
  - `split()` algorithm in string algo
  - string `tokenizer`
    - the result of tokenization is a sort of iterable container, compatible with the STL

Miscellaneous Boost Libraries
Tokenizer (2)

- **String tokenization: example with `boost::tokenizer`**

```
#include <boost/tokenizer.hpp>

char_separator<char> sep(":");
string s = getenv("PATH");
tokenizer<char_separator<char>> tok(s, sep);

list<string> li;
copy(tok.begin(), tok.end(), back_inserter(li));
```

  - Separators are individual characters
  - The separators can be dropped (by default) or kept in the tokens
  - Empty fields are dropped by default, but can be kept:

```
char_separator<char> sep(":", "", keep_empty_tokens);
```

TR1 and Boost Regular Expressions (`regex`)

- **Regular expression support in TR1 and Boost**
- **Regular expression syntax(es)**
- **Defining regular expressions**
- **Matching, searching, and replacing**
- **Regular expression iterators**
- **Regular expressions and UNICODE**

TR1 and Boost Regular Expressions (`regex`) Support in TR1 and Boost

- **Both Boost and TR1 define regular expression support (`regex`)**
- **As of gcc-8.1.x, GNU compilers do not implement `regex` in TR1**
  - If Boost is present, `tr1::regex` is in fact `boost::regex`
- **The definition in TR1 and the Boost implementation are almost identical**
  - Boost supports more regular expression syntaxes than `tr1`
- **As an extension, Boost `regex` supports UNICODE...**
  - provided that the (free) IBM library ICU is installed
- **We use `boost::regex` in the following examples**

```
#include <boost/regex.hpp>
```


TR1 and Boost Regular Expressions (`regex`) Regular Expression Syntaxes

- **TR1 supports 6 different (similar but incompatible) syntaxes**
  - POSIX *Basic Regular Expression* (BRE) and *Extended Regular Expression* (ERE) syntaxes
  - POSIX **awk**, **grep**, and **egrep** syntaxes
  - ECMAScript regular expression syntax, which is the default (and the richest)
- **We use ECMAScript**
  - We do not describe the whole ECMA syntax!
  - See the documentation for complements and differences, or Pete BECKER's book

TR1 and Boost Regular Expressions (`regex`) Regular Expression ECMA Syntax (1)

- **Usual elements**
  - Individual characters: `a b` ... `A B` ... `; :` ...
  - Wildcard: `.` (dot) stands for any character except newline
  - Character class: `[a-zA-C;,]` `[^a-zA-Z]`
  - Repetition: `a*` `a?` `[0-9]+` `[ab]{3}` `[0-9]{1,5}`
  - Group: `(ab)*`
  - Alternative: `(a|b)+`
  - Back reference: `([a-z]*)([0-9]+):\2\1`

TR1 and Boost Regular Expressions (`regex`) Regular Expression ECMA Syntax (2)

- **Predefined character classes**
  - Digits: `[[:digit:]]` `\d` `[[:d:]]`
  - Non digit: `[^[:digit:]]` `\D` `[^[:d:]]`
  - Spaces: `[[:space:]]` `\s` `[[:s:]]`
  - Non space: `[^[:space:]]` `\S` `[^[:s:]]`
  - Alphanum.: `[a-zA-Z0-9_]` `\w` `[[:w:]]`
  - Non alphanum.: `[^a-zA-Z0-9_]` `\W` `[^[:W:]]`
- **The exact definition depend on *regex traits* (in particular on the encoding and locale)**

TR1 and Boost Regular Expressions (`regex`) Regular Expression ECMA Syntax (3)

- **Examples of regular expressions within C/C++ literal strings**
  - **Beware**: within a literal string, character \ must be doubled

`"[a-zA-Z_][a-zA-Z0-9_]*"`	identifier
`"[[:alpha:]][[:alnum:]]*"`	idem
`"[[:alpha:]][\\w]*"`	idem
`"[-+]?\\d*(\\.\\d*)?"`	a float in fixed representation
`"(\\w+)\\s+\\1"`	a duplicated word separated by spaces
`"(\\w+|\\d+)\\s+\\1"`	a duplicated word or integer separated by spaces

TR1 and Boost Regular Expressions (`regex`) Defining Regular Expressions

- **Classes to encapsulate (compile...) a regular expression**

```
template <typename charT,
          typename traits = regex_traits<charT>>
class basic_regex;
typedef basic_regex<char> regex;
typedef basic_regex<wchar_t> wregex;
```

  - `traits` define necessary internal operations on `charT`
- **Construction of a regex from a C or C++ string**

```
regex re("[a-zA-Z_][a-zA-Z0-9_]*");
```

  - These constructors are `explicit`
  - A second parameter (*flags*) is optional: it mainly allows to choose the syntax of regular expressions and some parameters such as case sensitiveness...

```
regex re("[a-zA-Z_][a-zA-Z0-9_]*",
         regex_constants::perl);
```


TR1 and Boost Regular Expressions (`regex`) Matching (1)

- **(Exact) matching: `regex_match`**

```
regex re("(\\w+\\s*)*");
bool b;
b = regex_match("hello new world", re);    // true
b = regex_match("hello, new world!", re); // false
b = regex_match("hello new world!", re);  // false
```

  - The string must **completely** match the regular expression
- **Note on greediness**
  - By default, repetition operators `*` and `+` choose the **longest match**
    - thus, with string `"hello new world"`, the group `(\\w+\\s*)` matches the whole word `hello` plus the following space and not, for instance, `h` followed by no space, or `he` followed by no space...
  - It is possible to require a non greedy match (see later)

TR1 and Boost Regular Expressions (regex) Matching (2)

- **Parameters of `regex_match`**
  - Many forms of `regex_match`
    - Using `char*`, `strings`, iterators...
  - The last parameter (optional) contains *match flags*
    - They correspond to handling of some special conditions such as beginning or end of line, or depending on particular forms of regular expressions
    - All other matching functions take the same sort of flags as last parameter
  - Some forms include a `match_results` parameter to match sub-expressions (see `regex_search`)

TR1 and Boost Regular Expressions (regex) Searching (1)

- **Searching for sub-patterns: `regex_search`**

```
string s = "10U, 11u, 12, 13U, 14U, 15u";
regex re("(\\d+u)|(\\d+U)");
bool b = regex_search(s, re); // true
```

- **Identifying sub-patterns**

```
smatch m; // an array of sub-matches for string
if (regex_search(s, m, re)) {
  if (m[1].matched)
    cout << "use form in u\n";
  if (m[2].matched)
    cout << "use form in U\n";
}
```

  - The search stops at the first match
  - Output ⇒ `use form in U`

TR1 and Boost Regular Expressions (regex) Searching (2)

- **Match results and sub-matches**
  - Class `match_results`
    - An array of sub-matches

`m[0]`	the current match
`m[1]`	sub-match for sub-expression 1 in `regex`
`m[2]`	sub-match for sub-expression 2 in `regex`, etc.

  - Several forms depending on the type of strings that are scanned

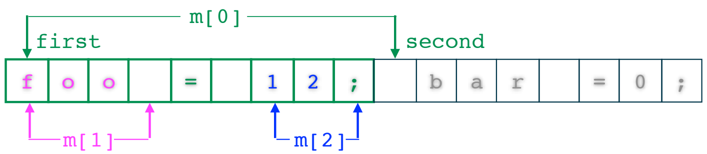
`cmatch`	for	`char*`
`wcmatch`	for	`wchar_t*`
`smatch`	for	`std::string`
`wsmatch`	for	`std::wstring`

  - Class `sub_match`
    - Each sub-match is a pair of iterators delineating the sub-match, plus a boolean `matched`

TR1 and Boost Regular Expressions (regex) Searching (3)

- **Match results and sub-matches (cont.)**

```
string s = "foo = 12; bar = 0;";
regex re("(\\w+) = (\\d+);");
smatch m;
bool b = regex_search(s, m, re);
```



TR1 and Boost Regular Expressions (regex) Searching (4)

- **Iterating on sub-matches**

```
string s = "10U, 11u, 12, 13U, 14U, 15u";
regex re("(\\d+u)|(\\d+U)");
smatch m;
int cntu = 0, cntU = 0;
string::const_iterator it = s.begin();
string::const_iterator end = s.end();
while (regex_search(it, end, m, re)) {
    if (m[1].matched)
        cntu++;
    else
        cntU++;
    it = m[0].second;
}
```


TR1 and Boost Regular Expressions (regex) Searching (5)

- **Revisiting greediness: greedy repetition**

```
string s = "aaa 12 bbbb 163";
smatch m;
regex re(".*(\\d+)");
string::const_iterator it = s.begin();
string::const_iterator end = s.end();
while (regex_search(it, end, m, re)) {
    if (m[1].matched) // useless
        cout << m[1].str() << endl;
    it = m[0].second;
}
```

Output ⇒

```
3
```


TR1 and Boost Regular Expressions (regex) Searching (6)

- **Revisiting greediness: non greedy repetition**

```
string s = "aaa 12 bbbb 163";
smatch m;
regex re(".*?(\\d+)");
string::const_iterator it = s.begin();
string::const_iterator end = s.end();
while (regex_search(it, end, m, re)) {
    if (m[1].matched) // useless
        cout << m[1].str() << endl;
    it = m[0].second;
}
```

Output ⇒

```
12
163
```


TR1 and Boost Regular Expressions (regex) Replacing

- **Text substitution: `regex_replace`**

```
regex re("(colo)(u)(r)", regex::icase);
string s = "Colour colours color Colourize";
cout << regex_replace(s, re, "$1$3");
```

Output ⇒

```
Color colors color Colorize
```

TR1 and Boost Regular Expressions (regex)
Regular Expression Iterators (1)

- **Using STL algorithms on sub-match collections**

```
struct regex_sum {
    int _sum;
    regex_sum() : _sum(0) {}

    // M will be a match_results
    template <typename M>
    void operator()(const M& m) {
        _sum += lexical_cast<int>(m[1].str());
    }
};

string s = "1, 2, 3, 4, 5, 6, 7, 8, 9, 10";
regex re("(\\d+),?");
sregex_iterator it(s.begin(), s.end(), re);
sregex_iterator end;
cout << for_each(it, end, regex_sum())._sum << endl; //55
```


TR1 and Boost Regular Expressions (regex)
Regular Expression Iterators (2)

- **Regex token iterators (`regex_token_iterator`)**
  - Similar to `regex_iterator` but can be used to split a string according to separators which are themselves regular expressions

```
vector<string> split(const string& s, const string& sep) {
  regex resep(sep);
  sregex_token_iterator it(s.begin(), s.end(), resep, -1);
  sregex_token_iterator end;
  vector<string> res;
  while (it != end)
    res.push_back(*it++);
  return res;
}

vector<string> v = split("aaa;--bbbb::;ccccc:;;-", "[-;:]+");
```

v: ⇒ `aaa bbbb ccccc`

TR1 and Boost Regular Expressions (regex)
Regular Expressions and UNICODE (1)

- **UNICODE and C++**
  - C++03 does not know about UNICODE
    - `wchar_t` is not guaranteed to be wide enough for UNICODE representation
    - There is no guarantee that the system will consider `wchar_t` as UNICODE
- **There exist third party UNICODE libraries**
  - Boost is able to use the ICU UNICODE library from IBM
  - UTF-8, UTF-16, or UTF-32 are supported through class `boost::u32regex`
- **C++2011 knows (a little) about UNICODE**
  - It can represent literal strings in UTF-8, UTF-16, or UTF-32
  - But it lacks general facilities for conversions, iterating, etc.

TR1 and Boost Regular Expressions (regex)
Regular Expressions and UNICODE (2)

- **A simple example of UNICODE regex**
  - The following program is supposed to be encoded in UTF-8

```
#include <boost/regex/icu.hpp>
// other usual includes
int main() {
    u32regex re =
       make_u32regex("(/?[^/]*)*/([^/]*)");
    smatch m;
    string s = "/été/être";
    if (u32regex_match(s, m, re)) {
       cout << m[2].str() << endl; // ⇒ être
    }
}
```


Advanced C++ Libraries and Introduction to Template Metaprogramming

Part 7

Boost Serialization Library

Serialization Library

- **Overview**
- **A simple example**
- **Pointer tracking**
- **Polymorphic class hierarchies**
- **STL collections**

Serialization Library Overview: Motivation

- **Save and restore C++ objects to or from files (archives)**
- **Minimal modification of classes**
- **Handle object sharing**
  - Pointer tracking and sharing
- **Handle polymorphism**
- **Compatible with STL collections**

Serialization Library Overview

- **Archive types**
  - Text archives
    - A compact, hardly readable format
  - xml archives
    - Readable (?) and verbose
    - More information than in a text archive
- **Data streams**
  - Output stream: used to save data

    ```
    oar << data;
    ```
  - Input data stream: used to restore (load) data

    ```
    iar >> data;
    ```

Serialization Library
A Simple Example (1)

- **A class to serialize**

```
class Date {

private:
    int _year, _month, _day;




public:
    Date() : _year(0), _month(0), _day(0) {};
    Date(int y, int m, int d) : _year(y), _month(m), _day(d) {}
    // other functions and operators
};
```


Serialization Library
A Simple Example (2)

- **Intrusive mode**

```
#include <boost/archive/xml_oarchive.hpp>
#include <boost/archive/xml_iarchive.hpp>
#define NVP(x) BOOST_SERIALIZATION_NVP(x)

class Date {
    friend class boost::serialization::access;
private:
    int _year, _month, _day;

    template <typename Archive>
    void serialize(Archive& ar, const unsigned int version) {
        ar & NVP(_year) & NVP(_month) & NVP(_day);
    }
public:
    Date() : _year(0), _month(0), _day(0) {};
    Date(int y, int m, int d) : _year(y), _month(m), _day(d) {}
    // other functions and operators
};
```

Allow access to private members

One function for both store and load

Serialization Library
A Simple Example (3)

- **Non intrusive mode**

```
#include <boost/archive/xml_oarchive.hpp>
#include <boost/archive/xml_iarchive.hpp>
#define NVP(x) BOOST_SERIALIZATION_NVP(x)

class Date {
private: public:
    int _year, _month, _day;
public:
    Date() : _year(0), _month(0), _day(0) {};
    Date(int y, int m, int d) : _year(y), _month(m), _day(d) {}
    // other functions and operators
};

template <typename Archive>
void serialize(Archive& ar, Date& dat,
               const unsigned int version) {
     ar & NVP(dat._year) & NVP(dat._month) & NVP(dat._day);
}
```

All members must be accessible

One function **outside the class** for both store and load

Serialization Library
A Simple Example (4)

- **Main program (both for intrusive and non intrusive)**

```
int main() {
     Date dat(2009, 11, 24);
    {   // Saving
        ofstream ofs("archive.xml");
        boost::archive::xml_oarchive oar(ofs);
        oar << NVP(dat);
    } // destructors close archive

     // Later… or in an other program

    {   // Restoring
        ifstream ifs("archive.xml");
        boost::archive::xml_iarchive iar(ifs);
        Date dat1;  // Note: default construction
        iar >> NVP(dat1);
        assert(dat == dat1);
    } // destructors close archive
}
```

Serialization Library
A Simple Example (5)

- **Format of the XML archive**

```
<?xml version="1.0" encoding="UTF-8"
      standalone="yes" ?>
<!DOCTYPE boost_serialization>

<boost_serialization
    signature="serialization::archive" version="5">

<dat class_id="0" tracking_level="0" version="0">
    <_year>2009</_year>
    <_month>11</_month>
    <_day>24</_day>
</dat>

</boost_serialization>
```


Serialization Library
A Simple Example (6)

- **Assigning XML tags**
  - When saving/restoring an object into/from an XML archive, one must provide a tag
  - This is done through a "name-value pair"

```
ar & make_nvp("my_tag", a_variable);
```

  - Usually, the tag is identical to the variable name: one can then use a predefined macro

```
ar & BOOST_SERIALIZATION_NVP(a_variable);
```

  - Since this macro name precludes readability, we always define

```
#define NVP(x) BOOST_SERIALIZATION_NVP(x)
ar & NVP(a_variable);
```

- **Tags are not used for text archives**
  - However, one can still use the previous macro, which ignores the tag in this case

Serialization Library
Pointer Tracking

```
struct A {
   int _i;
   template<class Archive>
   void serialize(Archive & ar, const unsigned int version) {
        ar & NVP(_i);
   }
   A(int i = 0) : _i(i) {}
};

typedef boost::shared_ptr<A> A_ptr; // also OK with A*
int main() {
   A_ptr pa1(new A());
   A_ptr pa2(pa1);
   oar << NVP(pa1) << NVP(pa2);
   // ...
   A_ptr qa1;
   A_ptr qa2;
   iar >> NVP(qa1) >> NVP(qa2);
   assert(qa1 == qa2);
   assert(qa1.use_count() == qa2.use_count() && qa1.use_count == 2);
}
```


Serialization Library
Polymorphic Class Hierarchies (1)

```
#include <boost/serialization/export.hpp>

class A {
    friend class boost::serialization::access;
    int _a;
public:
    A(int a) : _a(a) {}
    template <typename Archive>
    void serialize(Archive& ar, const unsigned int version) {
        ar & BOOST_SERIALIZATION_NVP(_a);
    }
    virtual void f() {cout << "A::f" << endl;}
};

class B : public A {
    friend class boost::serialization::access;
    int _b;
public:
    B(int a, int b) : A(a), _b(b) {}
    template <typename Archive>
    void serialize(Archive& ar, const unsigned int version) {
        ar & BOOST_SERIALIZATION_BASE_OBJECT_NVP(A);
        ar & BOOST_SERIALIZATION_NVP(_b);
    }
    virtual void f() {cout << "B::f" << endl;}
};
BOOST_CLASS_EXPORT(B) // register class
```

Serialization Library
Polymorphic Class Hierarchies (2)

```
int main() {
    A* pa = new B();
    {
        ofstream ofs("poly.xml");
        boost::archive::xml_oarchive oar(ofs);
        oar & BOOST_SERIALIZATION_NVP(pa);
    }

    A* qa;
    {
        ifstream ifs("poly.xml");
        boost::archive::xml_iarchive iar(ifs);
        iar & BOOST_SERIALIZATION_NVP(qa);
    }

    qa->f(); // virtually calls B::f()
}
```


Serialization Library
STL Containers

- **The C++ STL containers are serializable**

```
#include <boost/serialization/list.hpp>
#include <boost/serialization/deque.hpp>

list<A> la = {A(), A(), A()};
deque<A *> dqa = {new A(), new B(), new B()};
oar & NVP(la) & NVP(dqa);

list<A> la1;
deque<A *> dqa1;
iar & NVP(la1) & NVP(dqa1);

for_each(la1.begin(), la1.end(), bind(&A::f, _1));
for_each(dqa1.begin(), dqa1.end(), bind(&A::f, _1));
    // This one is polymorphic!
```


Advanced C++ Libraries and Introduction to Template Metaprogramming

Part 8

Computing with Types

Introduction to the
Boost Metaprogramming Library (MPL)

Computing with Types

- **Motivation; the Boost Metaprogramming Library (MPL)**
- **Characteristics of (template) metaprogramming in C++ MPL**
- **Example: dimensional analysis**
- **Overview of the MPL: compile time containers, iterators, and algorithms**
- **Evaluation of C++ metaprogramming**

Motivation — Boost MPL

- **Type traits elements, `enable_if` are examples of meta functions**
  - A meta-function operates on types (arguments or results)
  - Thus its evaluation is performed at compile-time
  - It may, or may not, be present/used at run time
- **To make metaprogramming more general and more accessible, Boost has introduced the MPL**
  - Metafunctions, lambdas, and high order programming to manipulate and compute with types (and integers) at compile-time
  - Compile time containers, iterators, and algorithms (inspired by the STL)

Characteristics of (Template) Metaprogramming in C++ MPL (1)

- **Metadata**
  - They are ***types***
  - Thus they are ***immutable*** (no assignment)
- **Programming style**
  - Functional programming
  - No assignment
  - No loops, no primitive control structures... except recursion and template specialization

Characteristics of (Template) Metaprogramming in C++ MPL (2)

- **Metafunction definition**
  - A nullary metafunction

    ```
    struct mf0 { typedef some_type type; };
    ```
  - A metafunction with 2 parameters

    ```
    template <typename T1, typename T2>
    struct mf2 { typedef some_type type; };
    ```
  - Numerical metafunctions

    ```
    template <typename T> struct nf1 {
         static const int value = . . .;
    };
    ```
- **Metafunction call**

  ```
  int f(mf0::type x) ...
  mf2<int, double>::type g() ...
  if (is_pointer<T>::value) ...
  ```


Characteristics of (Template) Using the MPL

- **Namespace `boost::mpl`**
- **The example programs of this course declare**

  ```
  using namespace std;
  namespace mpl = boost::mpl;
  using namespace placeholders;
  ```
  - Thus the elements of the mpl are in mpl::

    ```
    mpl::vector<...>   mpl::int_<3>   ...
    ```
    - On the slides we shall forget `mpl::`
  - The placeholders are simply _, _1, _2...
- **The MPL elements reside in a lot (a lot!) of `.hpp` files**

Example: Dimensional Analysis

- **Purpose**
  - Represent physical quantities together with their physical dimensions
    - Mass, length, time, velocity, energy, etc.
  - Enforce dimension constraints at compile time
    - Adding a mass to a length must not compile
  - Track dimensions at run time
    - The product of a mass by an acceleration is a force
- **Idea**
  - Represent physical dimensions as types
  - Associate its dimension type with each value
  - However, type computation is needed because of 2 and 3 above...

Example: Dimensional Analysis Representing Physical Dimensions (1)

- ***Système International*** **(SI)**
  - 7 fundamental dimensions : mass (**kg**), length (**m**), time (**s**), electrical intensity (**A**), temperature (**K**), amount of substance (**mol**), and luminous intensity (**cd**)
  - Here, we shall limit ourselves to the first 3: mass (*M*), length (*L*), and time (*T*)
- **It is possible to represent a dimension by an array of integers**

```
typedef int dimensions[3]; // 7 in reality
//                          M  L  T
const dimension mass =     {1, 0, 0};
const dimension length =   {0, 1, 0};
const dimension time =     {0, 0, 1};
```

  - A force (MLT^{-2}) would then be

```
const dimension force =    {1, 1, -2};
```

  - However, these are run time arrays, **not types**!

Example: Dimensional Analysis Representing Physical Dimensions (2)

- **Integral sequence wrapper**

```
vector<int_<e1>, int_<e2>, …, int_<en>>
```

  - or in a nicer form

```
vector_c<int, e1, e2, …, en>
```

  - A vector of types, each type being associated with an integer
    - each element similar to integral_constant from type traits
    - `int_` can be replaced by `bool_`, `long_`...
  - The elements `e1`, `e2`, ..., `en` must be compile time constants, here of type `int`
  - The overall result vector is a type
    - There is one different type for different values of the template parameters
  - Note the use of variadic templates, a C++11 extension

Example: Dimensional Analysis Representing Physical Dimensions (3)

- **Fundamental dimensions**

```
typedef vector_c<int, 1, 0, 0> Mass;     // M
typedef vector_c<int, 0, 1, 0> Length;   // L
typedef vector_c<int, 0, 0, 1> Time;     // T
```

- **Derived dimensions**

```
typedef vector_c<int, 0, 0, 0> Scalar;
typedef vector_c<int, 1, 1, -2> Force;
typedef vector_c<int, 0, 1, -1> Velocity;
typedef vector_c<int, 0, 1, -2> Acceleration;
```

- **All these types are different**
- **`vector_c` is an example of (meta)sequence, a sequence of types**

Example: Dimensional Analysis
Representing Physical Quantities

```
// D: the physical dimension type
// note that D is not directly used in the class

template <typename D>
struct quantity
{
    explicit quantity(double x = 0.0) : _value(x) {}

    double value() const {return _value;}
    // ...
private:
    double _value;
};

quantity<Force> f(10.0); // a force of 10N
```


Example: Dimensional Analysis
Add, Subtract, Compare...

```
template <typename D>
quantity<D>
operator+(quantity<D> x, quantity<D> y)
{
    return quantity<D>(x.value() + y.value());
}

quantity<Length> len1(3.5), len2(3.5), l;
quantity<Force> f(10.0);
quantity<Length> len;
len = len1 + len2; // OK
len = len1 + f;  // does not compile
```

- **Idem for subtraction, relational operators**
- **Simple enough for `ostream operator<<`**

Example: Dimensional Analysis
Multiply and Divide (1)

```
template <typename D1, typename D2>
quantity<??>
operator*(quantity<D1> x, quantity<D2> y)
{
    return quantity<??>(x.value() * y.value());
}
```

- **We need a type like `D1+D2`, where addition is element-wise...**

Example: Dimensional Analysis
Multiply and Divide (2)

- **(Meta)-algorithm `transform`**

```
transform<S1, S2, BinOp>
```

  - `S1` and `S2` are two type sequences with the same length
  - `BinOp` is a binary metafunction
  - The metafunction `transform` yields a *new* sequence produced by applying `BinOp` to the pairs of elements, one from each sequence
- **Meta-function `plus`**

```
plus<I1, I2>
```

  - `I1` and `I2` are types representing integral values (`int_`, `long_`...)
  - The metafunction `plus` yields a type representing the sum of the values associated with `I1` and `I2`

    plus<int_<i1>, int_<i2>> is plus<int_<i1+i2>>

  - Of course there exists also `minus`, `mult`, `div`, etc.

Example: Dimensional Analysis Multiply and Divide (3)

- **Dimensions of the result of multiplication**

```
template <typename D1, typename D2>
struct mult_dimensions :
    transform<D1, D2, plus<_1, _2>>
{};
```

- **Multiply operator**

```
template <typename D1, typename D2>
quantity<typename mult_dimensions<D1, D2>::type>
operator*(quantity<D1> x, quantity<D2> y)
{
    typedef typename mult_dimensions<D1, D2>::type dim_res;
    return quantity<dim_res>(x.value() * y.value());
}
```

  - Idem for divide...

Example: Dimensional Analysis Multiply and Divide (4)

- **Use of multiply**

```
quantity<Mass> m(10.0);
quantity<Acceleration> g(9.81);
cout << m * g << endl; // OK
```

- **But...**

```
quantity<Force> f;
f = m * g; // does not compile
```

  - The type built by `transform` is *not* a specialization of `vector_c`
    - although it contains the same integer values...
  - We need an implicit conversion...

Example: Dimensional Analysis Multiply and Divide (5)

```
template <typename D>
struct quantity {
    explicit quantity(double x = 0.0) : _value(x) {}

    double value() const {return _value;}

    template <typename D1>
    quantity(const quantity<D1>& q)
        : _value(q.value())
    {
        static_assert(equal<D, D1>::type::value,
                      "Bad conversion of dimensions");
    }
private:
    double _value;
};
```

- **`mpl:equal` checks two type sequences for equality, element-wise**

Overview of MPL

- **Data types**
  - Integral wrappers
    - transform integers into types
- **Metafunctions**
  - for integral wrappers
    - arithmetic
    - logical
    - bitwise
  - for type selection
  - for high order programming
  - miscellaneous
- **Type sequences**
  - containers for types
  - possibly extensible (insertion)
  - possibly with lazy evaluation
  - associated metafunctions
- **Iterators**
  - position in sequence
- **Algorithms**
  - apply an operation on a sequence

Overview of MPL
Data Types

- **Integral constant**
  - Nullary metafunction that returns itself
  - Associated with an integral compile time constant
  - Example: `int_<N>` is a class such that

  `int_<N>::value == N`
  `int_<N>::type` is `int_<N>`
  `int_<N>::value_type` is `int_<N>`

  - Also `bool_<TF>`, `long_<N>`, `size_t<N>`, `integral_c<T,N>`
- **Numeric metafunctions**
  - Example: `plus<T1, T2, ...>` is a class such that
    - `T1`, `T2`... must be integral constant types
    - `plus<T1, T2, ...>::type` is the integral constant type corresponding to the sum of the values of `T1`, `T2`, ...
  - Arithmetic: `plus`, `minus`...
  - Comparison: `less`, `equal_to`...
  - Logical: `and_`, `or_`, `not_`
  - Bitwise: `bitand_`, `shift_left`...

Overview of MPL
Sequences of Types (1)

- **Sequences**
  - `vector`, `list`, `deque`
    - `vector_c`, `list_c`, `deque_c` for integral constant wrappers
  - `set`, `map` (associative sequences)
  - `range_c`
- **Sequence metafunctions**
  - indexing: `at`, `at_c`
  - iterator interface: `begin`, `end`
  - accessors: `back`, `front`, `size`, `value_type`
  - insertion: `insert`, `insert_range`, `push_back`, `pop_back`, `push_front`, `pop_front`
  - erasing: `clear`, `erase`
  - associative sequences: `erase_key`, `has_key`, `key_type`

Overview of MPL
Sequences of Types (2)

- **`vector` and `vector_c`**

```
typedef vector<int_<0>, int_<1>, int_<2>> v012; // not nice
typedef vector_c<int, 0, 1, 2> vc012;           // nicer
STATIC_ASSERT(equal<v012, vc012, equal_to<_,_>>::value);
STATIC_ASSERT(not is_same<v012, vc012>::value);
```

  - The 2 types are different, although they correspond to the same integer sequence
  - Idem for `list_c` and `set_c`
- **Extending a sequence**

```
typedef push_back<v012, int_<3>> v0123;
typedef push_back<vc012, int_<3>> vc0123;
STATIC_ASSERT(equal<v0123, vc0123, equal_to<_,_>>::value);
STATIC_ASSERT(not is_same<v0123, vc0123>::value);
```


Overview of MPL
Sequences of Types (3)

- **Indexing**

```
typedef at_c<v0123, 2> int2;
STATIC_ASSERT(at_c<v0123, 2>::type::value == 2);
```

- **`range_c`**
  - `range_c<int, N1, N2>` creates a sequence of consecutive integers from `N1` (included) to `N2` (excluded)

```
typedef range_c<int, 0, 4> r0123;
STATIC_ASSERT(size<r0123>::type::value == 4);
STATIC_ASSERT(not equal<v0123, v0123,
equal_to<_,_>>::value);
```

  - A `range_c` sequence is ***not*** extensible

Overview of MPL
Sequences of Types (4)

- **Iterators**

```
typedef list<char, short, int, long, long long> types;
typedef begin<types>::type types_0;
STATIC_ASSERT(is_same<deref<types_0>::type, char>::value);
typedef advance<types_0, int_<2>>::type types_2;
STATIC_ASSERT(is_same<deref<types_2>::type, int>::value);
```

  - Metafunctions
    - move: `advance`, `next`, `prior`
    - compute distance: `distance`
    - iterator dereferencing: `deref`
    - sort of iterator: `iterator_category`

Overview of MPL
Algorithms (1)

- **Inserters**
  - `back_inserter`, `front_inserter`
- **Iteration**
  - `fold`, `iter_fold`, `reverse_fold`, `reverse_iter_fold`, `accumulate`
- **Query**
  - `find`, `find_if`, `contains`
  - `count`, `count_if`
  - `lower_bound`, `upper_bound`
  - `min_element`, `max_element`
  - `equal`
- **Transformation**
  - `copy`, `copy_if`, `transform`
  - `replace`, `replace_if`
  - `remove`, `remove_if`
  - `unique`, `partition`, `stable_partition`
  - All the above prefixed with `reverse_` (`reverse_copy`...)
  - `sort`

Overview of MPL
Algorithms: `for_each` (1)

- **Traversing the compile time/run time boundary: `for_each`**

```
for_each<seq>(fobj);
```

  - `seq` is an MPL sequence, and `fobj` a function object
  - for each type in `seq`, `for_each` invokes `fobj`, passing to it an instance of the type
    - the instance is *value initialized*
    - since value initialization does not work for references, `seq` cannot contains reference types (nor classes which are not default constructible...)

Overview of MPL
Algorithms: `for_each` (2)

- **Example: printing the elements of a sequence of types**

```
template <typename T>
struct type_printer {
    void operator()(T) {
        cout << typeid(T).name() << ' ';
    }
};
template <typename T> class A {};
typedef vector<int, double, string*, A<int>> types;
for_each<types>(type_printer());
```

  - Because of value initialization, type `A` must be complete (and default constructible) and `types` must not contain any reference
  - The result is not nice: with `g++` it is

```
i d PSs 1AIiE
```

Overview of MPL
Algorithms: `for_each` (3)

- **Fixing the `typeid()` problem (case of g++)**

```
template <typename T>
string type_to_string()
{
    int status;
    const char *name = typeid(T).name();
    char *demangled = abi::__cxa_demangle(name, 0, 0, &status);

    string res(status == 0 ? demangled : name);
    if (demangled)
        free(demangled); // !! __cxa_demangle uses malloc()!!
    return res;
}
```

  - However, `typeid()` looses reference indications...

Overview of MPL
Algorithms: `for_each` (3)

- **Fixing the value initialization problem**
  - Second form of `for_each`

    `for_each<seq, transf>(fobj);`

    - `seq` is an MPL sequence, `transf` an MPL transformation metafunction, and `fobj` a function object
    - for each type `T` in `seq`, `fobj` is invoked with a parameter the type of which is the result of the transformation of `T` by `transf` (`transf<T>::type`)

Overview of MPL
Algorithms: `for_each` (3)

- **Using a visitor pattern**

```
struct visit_type {  // a completely generic visitor
    template <typename Visitor>
    void operator()(Visitor) const {
        Visitor::visit();
    }
};

template <typename T>
struct print_visitor {
     static void visit() {
        cout << type_to_string<T>() << ' ';
    }
};
```

- **Note that `print_visitor<T>` does not instantiate any `T` object nor that `visit_type` require any one: only the type is passed along**
  - The value initialization problem disappears

Overview of MPL
Algorithms: `for_each` (4)

```
template <typename Seq>
struct print_sequence {
  print_sequence() {
       for_each<Seq, print_visitor<_>>(visit_type());
       cout << endl;
  }
};

typedef vector<int, double&, string, A<int>> types;
print_sequence<types>();
```

- **The result is**

  `int double std::string* A<int>`

  - The reference indication is lost: not yet perfect forwarding...

Overview of MPL
Type Selection

- **Using `if_` and logical operators: an example**

```
typedef transform<
    types,
    if_<
        or_<
            boost::is_scalar<_1>,
            boost::is_reference<_1>
        >,
        identity<_1>,        // then
        add_reference<_1> // else
    >
>::type ref_types;
```


Overview of MPL
Lazy Evaluation and Views

- **Lazy evaluation**
  - Computing the elements of a sequence ***on demand*** only
  - Here, searching an element first construct the whole transformed sequence

```
typedef contains<
    transform<seq, remove_cv<remove_reference<_>>>,
    int
>::type found;
STATIC_ASSERT(is_same<found, true_>::value); // if found
```

  - With the following, the transformed sequence is constructed on demand (the process stops when found)

```
typedef contains<
    transform_view<seq,
                   remove_cv<remove_reference<_>>
    int
>::type found;
```


Overview of MPL
High Order Programming

- **Just an example: applying the same metafunction twice**

```
template <typename F, typename T>
struct twice :
apply<F, typename apply<F, T>::type>
{};

struct pointerize {   // a metafunction class
    template <typename T>
    struct apply {
        typedef T *type;
    };
};

twice<pointerize, double> ppx; // double** ppx

typedef vector<int, double, string> types;
typedef transform<types, twice<pointerize, _>>::type pptypes;
at_c<pptypes, 2>::type pps;   // string **pps
```


Evaluation of Template Programming (1)

- **Pros**
  - Powerful type manipulation
  - Computing and dispatching at compile time speeds up execution
  - Domain specific languages on top of C++
  - Type aware macro-processing
- **Cons**
  - Nasty syntax, terrifying error messages
  - Difficult to debug, no development environment
  - Programming limitations: data can be types or integers only
  - Functional style is not natural to everybody

Evaluation of Template Programming (2)

- **Type traits is nice and simple enough**
- **`bind` and `function` are very convenient**
  - Used by other libraries like Boost or C++11 threads
- **Removal of *Concepts* from C++11 will tend to increase usage of `enable_if` and other "metaprogramming tricks"**
  - But *Concept (Lite)* will resurrect in C++14...

